DESCRIPTION

GAIT GENERATING DEVICE OF LEGGED MOBILE ROBOT

Technical Field

5   The present invention relates to a device for generating gaits suited not only to walking but also running of a legged mobile robot.

Background Art

10   Hitherto, a major object of generating gaits (desired gaits) for making a legged mobile robot, e.g., a bipedal mobile robot, carry out a traveling motion has been focused mainly on generating gaits (walking gaits) to make the robot effect a smooth walking motion. In recent years,
15 however, as the development of legged mobile robots advances, it has come to be desired to generate gaits that enable the robots not only to walk but to run also. Furthermore, it has come to be desired to generate gaits that enable the robots to move without troubles even on a
20 slippery floor (so-called low-μ path) on which a sufficient frictional force cannot be produced.

     Since the Chinese characters for "gait" include a character meaning "walking," the gait tends to be misinterpreted that the definition thereof is limited to
25 walking. However, "gait" originally presents a concept that includes running, as it is used as a term indicating a running mode of a horse, such as "trot."

A description will now be given of the difference between walking and running in terms of characteristics.

A traveling mode that includes an instant at which all legs are simultaneously floating is usually defined as

5   running. This definition, however, does not always make it possible to clearly distinguish between walking and running. For instance, in most humans, there are instants at which all legs float at the same time during fast jogging, whereas many humans have one of their legs always

10   in contact with the ground during slow jogging. It is somehow perceptually unreasonable to define fast jogging as running and slow jogging as walking.

Fig. 50 shows a pattern of vertical body positions and floor reaction force vertical components (a sum of

15   floor reaction force vertical components acting on right and left legs) in typical running, and Fig. 51 shows a pattern of vertical body positions and floor reaction force vertical components in typical walking.

A vertical body position/velocity means a vertical

20   position of a representative point of a body and a velocity thereof. A horizontal body position/velocity means a horizontal position of a representative point of the body and a velocity thereof. A vertical body position/velocity and a horizontal body position/velocity

25   together will be referred to as body position/velocity.

Strictly speaking, the "floor reaction force vertical component" should be described as "translational floor

reaction force vertical component" to distinguish it from a moment component about a vertical axis of a floor reaction force; however, the term is too long, so that the term "translational" will be omitted. Hereinafter, the

5   "translational floor reaction force horizontal component" will be described as "floor reaction force horizontal component," omitting "translational."

First, attention will be focused on the movement of the body. In walking, the body reaches a highest level at

10   the instant the body passes over a supporting leg, while it reaches a lowest level at this instant in running. In other words, the phase of a vertical motion pattern of the body reverses between walking and running.

Meanwhile, a floor reaction force remains relatively

15   constant in walking, whereas it considerably varies in running, the floor reaction force reaching its maximum at the moment the body passes over a supporting leg. Needless to say, the floor reaction force is zero at the instant when all legs are simultaneously floating. More

20   detailed observation reveals that a floor reaction force of a magnitude that is substantially proportional to a compression amount of the supporting leg is generated while running. In other words, it may be said that the legs are used like springs to jump for traveling while

25   running.

Slow jogging has the same body vertical motion phase as that of typical running. In addition, slow jogging

frequently includes no instants at which all legs are simultaneously floating; however, even in this case, a floor reaction force reaches substantially zero, although not completely zero, at an instant when a supporting leg

5 and an idle leg are switched.

Hence, distinguishing between walking and running on the basis of the aforesaid characteristics of the vertical motions of the body or floor reaction force patterns as described above may be more appropriate and perceptually

10 reasonable, because slow jogging is also regarded as running.

In particular, to distinguish between the two on the basis of a most characteristic aspect, running may be defined as a traveling mode in which the floor reaction

15 force becomes zero or substantially zero at the instant a supporting leg is switched, while walking may be defined as a traveling mode (a floor reaction force vertical component remaining relatively constant) other than that.

The present applicant has previously proposed, in PCT

20 Kokai publication WO/02/40224, an art for generating freely and in real time a gait of a legged mobile robot that includes a floor reaction force while substantially satisfying dynamic balance conditions (This means the conditions of balance among gravity, an inertial force,

25 and a floor reaction force of a desired gait. In a narrow sense, it means that the horizontal component of a moment about a desired ZMP by the resultant force of gravity and

an inertial force produced by a motion of a desired gait is zero. Detailed description will be given hereinafter). This art and a series of the control devices of legged mobile robots proposed by the present applicant in

5   Japanese Unexamined Patent Application Publication No. 10-86081, Japanese Unexamined Patent Application Publication No. 10-277969 can be applied to walking and also to running.

These arts, however, have not considered the

10   magnitudes of a vertical component of a floor reaction force moment about the ZMP of a desired gait. Hence, there has been a danger in that the vertical component of a floor reaction force moment becomes excessive, causing a frictional limitation to be exceeded and consequently

15   leading to a spin. The term "spin" refers to a state in which a yaw angle (a rotational angle about a vertical axis) velocity of an actual robot deviates from a desired yaw angular velocity.

When a robot walks on a floor surface having a high

20   friction coefficient (in this case, at least one leg is always in contact with the ground), a floor reaction force vertical component is always substantially equivalent to a robot's own weight, thus providing a higher limit of a frictional force (i.e., the vertical component of a floor

25   reaction force moment). This makes the robot resistant to spin.

In running, however, there are cases where the floor

reaction force vertical component becomes zero or close to zero; hence, in such a case, the limit of the moment vertical component of the frictional force of a floor surface becomes zero or close to zero even if a friction coefficient is high. Accordingly, there has been a danger in that a floor reaction force moment vertical component of a desired gait exceeds a limit, causing a spin and a fall.

Further, even in the case of walking, there has been a danger in that a robot spins and falls if a floor has a low friction coefficient.

Meanwhile, the present applicant has previously proposed a technique, in which an arm is swung so as to cancel a moment vertical component generated by anything other than arms in a desired gait in, for example, PCT application PCT/JP02/13596.

In this case, the moment vertical component of a desired gait will be substantially zero; however, if the robot travels, severely swinging its legs, it will also swing its arms severely.

Generally, in a human-like robot, the mass of its arms is smaller than that of its legs. Hence, in order to completely cancel a moment vertical component, it is necessary to swing the arms more severely than the legs.

However, the motion range of the arms is limited and the torque and speed of the actuators of the arms are also limited. Therefore, if the robot travels, severely

swinging its legs, there have been some cases where a moment vertical component cannot be fully canceled by the arms.

Furthermore, there has been a danger in that, if arms are swung to cancel out a moment vertical component produced by anything other than arms in a desired gait, then the center of arm swing is gradually offset, causing the swings of the right and left arms to be asymmetrical. Specifically, to make a left turn, if a robot swings its arms to fully offset a moment vertical component generated by anything other than arms, then the left arm is swung more toward the front and swung less toward the rear, while the right arm is swung less toward the front and swung more toward the rear in order to offset the change in an angular momentum caused by the legs and the body having turned to the left. This may cause the left arm to reach a motion limit of the swing toward the front, and the right arm to reach a motion limit of the swing toward the rear.

Furthermore, if a motion is made to restore the center of the arm swing so as to prevent the swings of the right and left arms from becoming asymmetrical, then a floor reaction force moment vertical component is generated. This in turn causes a floor reaction force moment vertical component of a desired gait to exceed a limit, possibly causing the robot to spin.

Accordingly, an object of the present invention is to

provide a gait generating device which solves the problems described above and which is capable of generating further ideal gaits regardless of the types of gaits, such as walking and running, and a friction condition of a floor

5 surface.

More specifically, an object of the present invention is to provide a gait generating device capable of generating gaits that make it possible to prevent a robot from spinning and falling caused by the spinning,

10 considering limitation of a moment vertical component of the force of a friction between the robot and a floor surface. Another object is to provide a gait generating device capable of generating a gait motion pattern that satisfies a dynamic balance condition even in a leg-

15 floating period or even if the limit of a moment vertical component of a frictional force is extremely low. Still another object is to prevent lateral asymmetry of a desired gait from increasing so as to secure continuity of a motion.

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Disclosure of Invention

To fulfill the aforesaid objectives, in a gait generating device for generating a desired gait of a legged mobile robot that travels by moving a plurality of

25 legs extended from its body, a gait generating device of a legged mobile robot in accordance with the present invention is provided with a permissible range setting

means for setting a permissible range of a restriction object amount, the restriction object amount being a vertical component of a floor reaction force moment to be applied to the robot or a component of the floor reaction

5   force moment in floor surface normal line direction, or a vertical component of an angular momentum changing rate of the robot or a component of the angular momentum changing rate in floor surface normal line direction, a provisional motion determining means for determining a provisional

10   motion of the desired gait such that a resultant force of a gravity and an inertial force acting on the robot satisfies a predetermined dynamic balance condition on a predetermined dynamic model, and a provisional motion correcting means for correcting the provisional motion to

15   determine the motion of a desired gait by changing the changing rate of an angular momentum of the robot from the provisional motion, while limiting the restriction object amount to the permissible range on the dynamic model if the restriction object amount defined by the provisional

20   motion of the desired gait deviates from the permissible range (a first invention).

       According to the present invention (the first invention), if the restriction object amount defined by the provisional motion of a desired gait deviates from the

25   permissible range, the motion of the desired gait is determined by correcting the provisional motion by changing the changing rate of an angular momentum of a

robot from the provisional motion, while limiting the restriction object amount to the permissible range on the dynamic model. Thus, the motion of a desired gait is generated, while limiting the restriction object amount to the permissible range. The restriction object amount is proportional or substantially proportional to the moment vertical component of the friction force between a robot and a floor surface. Therefore, the present invention (the first invention) is capable of generating a gait that makes it possible to prevent a robot from spinning and falling caused by the spinning, taking the restriction of the moment vertical component of a frictional force into account.

In the first invention, the angular momentum changing rate that is changed to limit the restriction object amount to the permissible range is, for example, the vertical component of the angular momentum changing rate or the component thereof in floor surface normal line direction.

In the first invention, the dynamic balance condition is, for example, a condition under which the horizontal component of a moment (a component other than the vertical component of the moment) generated about a predetermined point (e.g., a desired ZMP) on a floor surface by the resultant force of a gravity and an inertial force acting on the robot on a predetermined dynamic model satisfies a predetermined dynamic balance condition matches or

substantially matches a predetermined desired floor reaction force moment horizontal component, or a condition under which a translational force vertical component of the resultant force matches or substantially matches a predetermined desired translational floor reaction force vertical component. Of these dynamic balance conditions, the former dynamic balance condition is important for generating a gait that ensures stable motion (free of the danger of falling) of a robot, while the latter dynamic balance condition is important for generating a gait that ensures smooth running of the robot.

The permissible range of a restriction object amount may be set, considering the type of gait, the period of gait, and the frictional force that can be produced by floor, and the permissible range may be set to zero (both an upper limit value and a lower limit value of the permissible range may be zero). For example, in the case of a running gait having a period during which all legs of a robot float, the permissible range in the floating period may be set to zero.

In the first invention, a motion to be corrected by the provisional motion correcting means is preferably the motion of a body of the robot or an arm extended from the body (a second invention).

According to the second invention, the provisional motion can be corrected while minimizing the correction of a motion that influences the dynamic balance condition.

In the first invention, to be more specific, in the motion of the body of the robot or the motion of an arm extended from the body, the motion to be corrected by the provisional motion correcting means is preferably a motion that changes the vertical component of the angular momentum changing rate of the robot or the component of the angular momentum changing rate in floor surface normal line direction while substantially maintaining the position of the center-of-gravity of the robot at the position of the center-of-gravity determined by the provisional motion (a third invention).

According to the third invention, the provisional motion can be corrected while substantially maintaining the translational floor reaction force or the horizontal component of a floor reaction force moment acting on the robot at the one corresponding to the provisional motion. Hence, it is possible to determine the motion of a desired gait so that the restriction object amount remains in a permissible range by correcting the provisional motion of the body or an arm of the robot, while substantially satisfying the dynamic balance condition. Therefore, it is possible to generate a motion pattern of a gait that satisfies a dynamic balance condition even in a floating period or when the limitation of a moment vertical component of a frictional force is extremely low.

In these first to third inventions, if the robot is a robot equipped with two arms extended from the right and

left sides of the body, then the motion to be corrected by the provisional motion correcting means is preferably a motion for moving the two arms forward and backward relative to the robot in opposite directions from each other (a fourth invention).

The fourth invention facilitates the correction of the provisional motion.

In the first to the fourth inventions, if the desired gait is a gait in which a landing period during which at least one leg of the robot is landed and a floating period during which all legs are floated in the air are alternately repeated, then the permissible range is set to substantially zero at least during the floating period (a fifth invention).

With this arrangement, the motions of a desired gait for the landing period and also for the floating period can be properly determined.

Preferably, the first to the fifth inventions is equipped with a desired vertical component determining means for determining a desired vertical component of a translational floor reaction force of the robot or a desired vertical component of a total center-of-gravity acceleration or a desired vertical component of a body acceleration, wherein the permissible range setting means sets the permissible range on the basis of a desired vertical component determined by the desired vertical component determining means (a sixth invention).

More specifically, the moment vertical component or the component in floor surface normal line direction of the friction force between a robot and a floor surface is substantially proportional to a translational floor

5   reaction force vertical component. The translational floor reaction force vertical component is proportional to the sum of the total center-of-gravity acceleration vertical component of the robot and a gravitational acceleration. Furthermore, if, for example, the mass of

10   the legs of the robot is sufficiently smaller than the mass of the body, then the translational floor reaction force vertical component is substantially proportional to the sum of a body acceleration vertical component and a gravitational acceleration. Hence, the permissible range

15   of a pattern suited to a translational floor reaction force vertical component that is desired to be generated by the robot can be set by determining a desired vertical component of a translational floor reaction force of the robot or a desired vertical component of a total center-

20   of-gravity acceleration or a desired vertical component of a body acceleration, and then by setting the permissible range on the basis of the determined desired vertical component.

In the sixth invention, the provisional motion

25   determining means will determine the provisional motion such that the desired vertical component determined by the desired vertical component determining means is satisfied,

that is, a translational floor reaction force vertical component of the robot (the translational floor reaction force vertical component that matches the vertical component of the resultant force of an inertial force of a

5   provisional motion and gravity) or a total center-of-gravity acceleration vertical component or a body acceleration vertical component agrees or substantially agrees with the desired vertical component determined by the desired vertical component determining means. In

10   other words, this means that a provisional motion is determined such that the vertical component of the resultant force of the inertial force of the provisional motion and the gravity matches or substantially matches a desired translational floor reaction force vertical

15   component corresponding to the desired vertical component determined by the desired vertical component determining means on the dynamic model.

In the aforesaid first to the sixth inventions, the dynamic model is preferably a dynamic model that describes

20   at least the relationship between a motion to be corrected by the provisional motion correcting means and a floor reaction force as a relationship between a rotational motion of a flywheel, which is rotative about a vertical axis or a floor surface normal line axis, and a floor

25   reaction force (a seventh invention).

With this arrangement, a motion to be corrected will correspond to a rotational motion of the flywheel that

independently changes only a floor reaction force moment about the vertical axis or the floor surface normal line axis, thus permitting easy computation for correcting a provisional motion with a less amount of computation.

5   Furthermore, in the first to the seventh inventions described above, the provisional motion correcting means ideally determines a motion of the desired gait such that the motion of the robot to be corrected if the restriction object amount deviates from the permissible range is

10   approximated or matched to a predetermined reference motion trajectory in a predetermined period during which the restriction object amount determined by the provisional motion lies in the permissible range (e.g., a period during which the permissible range is sufficiently

15   large)(an eighth invention).

According to the eighth invention, the motion of a robot to be corrected can be approximated or matched to the ideal reference motion trajectory during the predetermined period in which the restriction object

20   amount does not deviate from the permissible range, that is, the period in which a sufficient frictional force can be produced between contact surfaces of the robot and the floor surface. As a result, it is possible to prevent the motion of the robot to be corrected from changing into a

25   motion with an extreme bias. In other words, it is possible to prevent the lateral asymmetry of the motion of a desired gait from increasing, ensuring the continuity of

the motion. If a gait that alternately repeats the floating period and the landing period is generated, as in the fifth invention, then the predetermined period will be in the landing period.

5   In the first to the eighth inventions, preferably, the desired gait to be generated has a current time gait generated for each predetermined period to be used for an actual motion of the robot, and a normal gait, which is a virtual cyclic gait following each current time gait and

10   which is used for generating the current time gait, and the processing of the provisional motion determining means and the provisional motion correcting means is carried out when generating the current time gait and/or a normal gait following the current time gait (a ninth invention).

15   In the ninth invention, the processing of the provisional motion determining means and the provisional motion correcting means is carried out in generating a current time gait and/or a normal gait, thus making it possible to generate an appropriate current time gait

20   and/or normal gait in which a restriction object amount does not deviate from a permissible range. A normal gait is a proper gait as the gait following a current time gait, and the current time gait is generated such that it is continued or approximated to a normal gait, satisfying a

25   condition in which the restriction object amount remains within a permissible range or satisfying the dynamic balance condition.

In the ninth invention, the permissible range setting means preferably sets the permissible range of the current time gait and the permissible range of the normal gait following the current time gait on the basis of a required

5 parameter of the current time gait (e.g., the parameter that defines the landing position/posture of the distal portion of each leg or expected landing time)(a tenth invention).

With this arrangement, an ideal normal gait that

10 matches a current time gait can be generated.

To be more specific, in the tenth invention, if the legged mobile robot is a bipedal mobile robot having two legs, then the required parameters ideally include the parameters that define the landing position/posture for

15 two steps of the distal portions of the legs of the bipedal mobile robot and a parameter that defines the gait cycles of a first step and a second step (an eleventh invention).

This arrangement makes it possible to determine a

20 normal gait that follows a current time gait by using the same type of mode (a mode, such as walking or running) as that of the current time gait, and to determine an ideal normal gait (a gait free from divergence) that follows the current gait. Thus, a current time gait capable of

25 reliably securing stability when a robot travels can be generated.

Brief Description of the Drawings

Fig. 1 is a diagram schematically showing a general construction of a bipedal mobile robot as a legged mobile robot in an embodiment of the present invention, Fig. 2 is a diagram showing a structure of a distal portion of a leg of the robot shown in Fig. 1, Fig. 3 is a block diagram showing a construction of a control unit provided in the robot shown in Fig. 1, and Fig. 4 is a block diagram showing a functional construction of the control unit. Fig. 5 is a diagram for explaining a running gait generated in the embodiment, Fig. 6 is a graph showing an example of a vertical component trajectory of a desired floor reaction force, Fig. 7 shows graphs illustrating examples of an X component and a Y component of a desired ZMP trajectory, Fig. 8 is a diagram for explaining a body translational mode of a robot, Fig. 9 is a diagram for explaining a body inclination mode of the robot, Fig. 10 is a diagram for explaining a body yaw rotation mode of the robot, Fig. 11(a) is a diagram for explaining an antiphase arm swing mode of the robot in a plan view and Fig. 11(b) is a diagram for explaining an antiphase arm swing mode of the robot in a side view, and Fig. 12 is a diagram for explaining a dynamic model used in the embodiment. Fig. 13 is a flowchart showing a main routine processing of a gait generating device in the embodiment, Fig. 14 is a diagram for explaining a divergence state of the robot, Fig. 15 is a flowchart showing a subroutine

processing of S022 of Fig. 13, Fig. 16 is a diagram for explaining a normal gait and a supporting leg coordinate system, Fig. 17 is a diagram illustrating a body trajectory of the normal gait and the supporting leg

5   coordinate system, Fig. 18 is a graph showing an example of a reference antiphase arm swing angle, Fig. 19 is a graph showing a setting example of a desired floor reaction force vertical component trajectory in a normal gait, Fig. 20 is a graph showing a setting example of a

10   floor reaction force horizontal component permissible range in a normal gait, Fig. 21 is a graph showing a setting example of a floor reaction force moment vertical component permissible range in the normal gait, and Fig. 22 is a graph showing a setting example of the desired ZMP

15   trajectory in the normal gait. Fig. 23 is a flowchart showing subroutine processing of S024 in Fig. 13, Fig. 24 is a flowchart showing subroutine processing of S208 in Fig. 23, Fig. 25 is a flowchart showing subroutine processing of S306 in Fig. 24, and Fig. 26 is a flowchart

20   showing subroutine processing of S412 in Fig. 25. Fig. 27 is a graph showing an example of a floor reaction force horizontal component in which a permissible range is not considered, Fig. 28 is a graph showing an example of the floor reaction force horizontal component in which a

25   permissible range is considered, Fig. 29 is a graph showing an example of a body inclination angular acceleration, Fig. 30 is a graph showing an example of a

body inclination restoring moment ZMP-converted value for restoring a body inclination angle of the robot, Fig. 31 is a graph showing an example of a body inclination angular acceleration in which the body inclination

5   restoring moment ZMP-converted value is reflected, Fig. 32 is a graph showing an example of a floor reaction force moment vertical component in which a permissible range is not considered, Fig. 33 is a graph showing an example of a floor reaction force moment vertical component in which

10   the permissible range is considered, Fig. 34 is a graph showing an example of an antiphase arm swing moment, Fig. 35 is a graph showing an antiphase arm swing angular acceleration corresponding to the antiphase arm swing moment shown in Fig. 34, Fig. 36 is a graph showing an

15   example of an antiphase arm swing restoring angular acceleration for restoring an antiphase arm swing angle, Fig. 37 is a graph showing an antiphase arm swing restoring moment corresponding to an antiphase arm swing restoring angular acceleration shown in Fig. 36, and Fig.

20   38 is a graph showing a floor reaction force moment vertical component formed by combining the floor reaction force moment vertical component shown in Fig. 33 and the antiphase arm swing restoring moment shown in Fig. 37. Fig. 39 is a flowchart showing subroutine processing of

25   S026 in Fig. 13, Fig. 40 is a graph showing a setting example of a floor reaction force horizontal component permissible range of a current time gait, Fig. 41 is a

graph showing a setting example of a floor reaction force moment vertical component permissible range of the current time gait, Fig. 42 is a flowchart showing subroutine processing of S028 in Fig. 13, Fig. 43 is a flowchart showing subroutine processing of S702 in Fig. 42, Fig. 44 is a graph showing examples of a provisional desired ZMP of the current time gait, a ZMP correction amount, and a desired ZMP after correction, Fig. 45 is a flowchart showing subroutine processing of S030 in Fig. 13, and Fig. 46 is a flowchart showing subroutine processing of S1412 in Fig. 45. Fig. 47 is a graph showing a relationship between normal gaits and desired gaits relative to body position trajectories, Fig. 48 is a diagram showing another example of a body inclination mode (body inclination about waist), Fig. 49 is a diagram for explaining another example of a dynamic model, Fig. 50 is a diagram showing a relationship between the position of the body in a vertical direction and a floor reaction force vertical component in a running gait of the robot, and Fig. 51 is a diagram showing a relationship between the position of the body in a vertical direction and a floor reaction force vertical component in a walking gait of the robot.

Best Mode for Carrying Out the Invention

Referring now to the accompanying drawings, a gait generating device of a legged mobile robot according to an

embodiment of the present invention will be explained. As
the legged mobile robot, a bipedal mobile robot will be
used as examples.

Fig. 1 is a schematic diagram generally showing a
5   bipedal mobile robot representing a legged mobile robot
according to the embodiment.

As shown in the figure, a bipedal mobile robot
(hereinafter referred to as "the robot") 1 is equipped
with a pair of right and left legs (leg links) 2, 2
10   provided such that they extend downward from a body (a
base body of the robot 1) 3. The two legs 2, 2 share the
same construction, each having six joints. The six joints
of each leg are comprised of, in the following order from
the body 3 side, joints 10R, 10L (symbols R and L meaning
15   correspondence to the right leg and the left leg,
respectively; the same will be applied hereinafter) for
swinging (rotating) a hip (waist)(for rotating in a yaw
direction relative to the body 3), joints 12R, 12L for
rotating the hip (waist) in a roll direction (about an X
20   axis), joints 14R, 14L for rotating the hip (waist) in a
pitch direction (about a Y axis), joints 16R, 16L for
rotating knees in the pitch direction, joints 18R, 18L for
rotating ankles in the pitch direction, and joints 20R,
20L for rotating the ankles in the roll direction.

25   A foot (foot portion) 22R (L) constituting a distal
portion of each leg 2 is attached to the bottoms of the
two joints 18R (L) and 20R (L) of the ankle of each leg 2.

The body 3 is installed at the uppermost top of the two legs 2, 2 through the intermediary of the three joints 10R (L), 12R (L) and 14R (L) of the hip of each leg 2. A control unit 60 or the like, which will be discussed in detail hereinafter, is housed inside the body 3. For convenience of illustration, the control unit 60 is shown outside the body 3 in Fig. 1.

In each leg 2 having the aforesaid construction, a hip joint (or a waist joint) is formed of the joints 10R (L), 12R (L) and 14R (L), the knee joint is formed of the joint 16R (L), and the ankle joint is formed of the joints 18R (L) and 20R (L). The hip joint and the knee joint are connected by a thigh link 24R (L), and the knee joint and the ankle joint are connected by a crus link 26R (L).

A pair of right and left arms 5, 5 is attached to both sides of an upper portion of the body 3, and a head 4 is disposed at a top end of the body 3. Each arm 5 is provided with a shoulder joint composed of three joints 30R (L), 32R (L), and 34R (L), an elbow joint composed of a joint 36 R(L), a wrist joint composed of a joint 38R (L), and a hand 40R (L) connected to the wrist joint. The head 4 is not directly connected to the topic of the present invention, so that detailed explanation thereof will be omitted.

According to the construction described above, the foot 22R (L) of each leg 2 is given six degrees of freedom relative to the body 3. During a travel, such as walking,

of the robot 1, desired motions of the two feet 22R and 22L can be accomplished by driving 6*2=12 joints of the two legs 2, 2 together ("*" in the present description denotes multiplication as scalar calculation, while it denotes an outer product in vector calculation) at appropriate angles. This arrangement enables the robot 1 to arbitrarily move in a three-dimensional space. Furthermore, each arm 5 can perform a motion, such as arm swinging, by rotating its shoulder joint, the elbow joint, and the wrist joint.

As shown in Fig. 1, a publicly known six-axis force sensor 50 is provided between the ankle joints 18R (L), 20R (L) and the foot 22R (L) of each leg 2. The six-axis force sensor 50 detects primarily whether the foot 22R (L) of each leg 2 is in contact with the ground, and a floor reaction force (landing load) acting on each leg 2, and it outputs detection signals of three-direction components Fx, Fy, and Fz of a translational force of the floor reaction force and three-direction components Mx, My, and Mz of a moment to the control unit 60. Furthermore, the body 3 is equipped with a posture sensor 54 for detecting an inclination angle of the body 3 relative to a Z-axis (vertical direction (gravitational direction)) and an angular velocity thereof, and a rotational angle (yaw angle) of the body 3 about the Z-axis and an angular velocity thereof, detection signals thereof being output from the posture sensor 54 to the control unit 60. The

posture sensor 54 is provided with a three-axis direction accelerometer and a three-axis direction gyro sensor, which are not shown. These detection signals of these sensors are used to detect posture angles (an inclination angle and a yaw angle) of the body 3 and an angular velocity thereof, and also used to estimate a self position/posture of the robot 1. Although detailed structures are not shown, each joint of the robot 1 is provided with an electric motor 64 (refer to Fig. 3) for driving the joint, and an encoder (rotary encoder) 65 (refer to Fig. 3) for detecting a rotational amount of the electric motor 64 (a rotational angle of each joint). Detection signals of the encoder 65 are output from the encoder 65 to the control unit 60.

Furthermore, although not shown in Fig. 1, a joystick (operating device) 73 (refer to Fig. 3) is provided at an appropriate position of the robot 1. The joystick 73 is constructed in such a manner that a request regarding a gait of the robot 1, such as a request for turning the robot 1 that is traveling straight, is input to the control unit 60 as necessary by operating the joystick 73.

Fig. 2 is a diagram schematically showing a basic construction of a distal portion (including each foot 22R (L)) of each leg 2 in the embodiment. As shown in the diagram, a spring mechanism 70 is installed between each foot 22R (L) and the six-axis force sensor 50, and a foot sole elastic member 71 made of rubber or the like is

bonded to a foot sole (the bottom surface of each foot 22R
(L)). These spring mechanism 70 and the foot sole elastic
member 71 constitute a compliance mechanism 72. The
spring mechanism 70, which will be discussed in detail

5   later, is constructed of a square guide member (not shown),
which is installed on the upper surface of the foot 22R
(L), and a piston-shaped member (not shown) installed
adjacently to the ankle joint 18R (L) (the ankle joint 20R
(L) being omitted in Fig. 2) and the six-axis force sensor

10   50, and housed in the guide member through the
intermediary of an elastic member (rubber or spring) so
that it may be jogged.

The foot 22R (L) indicated by a solid line shown in
Fig. 2 is in a state where it is subjected to no floor

15   reaction force. When each leg 2 is subjected to a floor
reaction force, the spring mechanism 70 and the foot sole
elastic member 71 of the compliance mechanism 72 flex,
causing the foot 22R (L) to shift to the position/posture
illustrated by a dashed line in the figure. The structure

20   of the compliance mechanism 72 is important not only to
ease a landing impact but also to enhance controllability,
as explained in detail in, for example, Japanese
Unexamined Patent Publication Application No. 5-305584
previously proposed by the present applicant.

25   Fig. 3 is a block diagram showing a construction of
the control unit 60. The control unit 60 is comprised of
a microcomputer, and includes a first calculator 90 and a

second calculator 92 formed of CPUs, an A/D converter 80,

a counter 86, a D/A converter 96, a RAM 84, a ROM 94, and

a bus line 82 for transferring data among them. In the

control unit 60, output signals of the six-axis force

5   sensor 50 of each leg 2, the posture sensor 54 (an

accelerometer and a rate gyro sensor), the joystick 73,

etc. are converted into digital values by the A/D

converter 80 and sent to the RAM 84 via the bus line 82.

Outputs of the encoder 65 (rotary encoder) of each joint

10   of the robot 1 are supplied to the RAM 84 via the counter

86.

As will be discussed hereinafter, the first

calculator 90 generates desired gaits, calculates a joint

angle displacement command (a command value of a

15   displacement angle of each joint or a rotational angle of

each electric motor 64), and sends the calculation result

to the RAM 84. The second calculator 92 reads the joint

angle displacement command and an actual measurement value

of a joint angle detected on the basis of an output signal

20   of the encoder 65 from the RAM 84 to calculate a

manipulated variable required for driving each joint, and

outputs the calculated variable to the electric motor 64

for driving each joint through the intermediary of the D/A

converter 96 and a servo amplifier 64a.

25   Fig. 4 is a block diagram showing the entire

functional construction of a control device of the legged

mobile robot in accordance with the embodiment. A portion

except for the "actual robot" in Fig. 4 is constituted by processing functions implemented by the control unit 60 (primarily the functions of the first calculator 90 and the second calculator 92). In the following explanation, the symbols R and L will be omitted as long as it is not particularly necessary to discriminate right and left of the legs 2 and the arms 5.

The explanation will now be given. The control unit 60 is equipped with a gait generating device 100 for generating desired gaits of the robot 1 freely in real time and outputting them. The functions of the gait generating device 100 constitute individual means of the present invention. A desired gait output by the gait generating device 100 is constituted of a desired body position/posture trajectory (trajectory of a desired position and a desired posture of the body 3), a desired foot position/posture trajectory (trajectory of a desired position and a desired posture of each foot 22), a desired arm posture trajectory (trajectory of a desired posture of each arm 5), a desired total floor reaction force central point (desired ZMP) trajectory, and a desired total floor reaction force trajectory. If a movable part relative to the body 3 is provided in addition to the legs 2 and the arms 5, then a desired position/posture trajectory of the movable part is added to the desired gait.

Here, the term "trajectory" in the above gait means a temporal change pattern (time series pattern), and may be

referred to as "pattern" in place of "trajectory" in the following explanation. Furthermore, a "posture" means a spatial orientation. Specifically, for example, a posture of a body is represented by an inclination angle of the

5   body 3 in the roll direction (about the X-axis) relative to the Z-axis (vertical axis), an inclination angle of the body 3 in the pitch direction (about the Y-axis), and a rotational angle (yaw angle) of the body 3 in the yaw direction (about the Z-axis). A foot posture is

10   represented by means of a spatial azimuth of two axes fixedly set on each foot 22. In the present description, a body posture may be referred to as a body posture angle.

In the following explanation, the term "desired" will be frequently omitted when there is no danger of

15   misunderstanding. Furthermore, among gaits, those gaits related to constituent elements other than those related to a floor reaction force, that is, the gaits related to motions of the robot 1, such as a foot position/posture and a body position/posture, will be collectively referred

20   to as "motion." A floor reaction force (floor reaction force comprised of a translational force and a moment) acting on each foot 22 is referred to as "each-foot floor reaction force", and a resultant force of the "each-foot floor reaction forces" of all (two) feet 22R and 22L of

25   the robot 1 will be referred to as a "total floor reaction force". In the following explanation, however, each-foot floor reaction force will hardly be referred to, so that

"floor reaction force" will be handled as having the same meaning as "total floor reaction force" unless otherwise specified.

A desired floor reaction force is generally expressed by a point of action and a translational force and the moment acting on the point. The point of action may be set at any location, so that innumerable expressions are possible for the same desired floor reaction force. If, however, a desired floor reaction force is expressed using especially a desired floor reaction force central point (a desired position of the central point of a total floor reaction force) as the point of action, then the moment component of the desired floor reaction force will be zero except for a vertical component (the moment about the vertical axis (Z-axis)). In other words, the horizontal component of the moment of the desired floor reaction force about the desired floor reaction force central point (the moment about the horizontal axis (the X-axis and the Y-axis)) will be zero.

In the case of a gait that satisfies dynamic balance conditions, a ZMP calculated from a desired motion trajectory of the robot 1 (a point at which the moment of a resultant force of an inertial force and gravity calculated from the desired motion trajectory acts about the point becomes zero except for a vertical component) agrees with a desired floor reaction force central point. Therefore, providing a desired ZMP trajectory may be

regarded as equivalent to providing a desired floor reaction force central point trajectory (refer to, for example, PCT Kokai publication WO/02/40224 by the present applicant, for more detail).

5   From the background described above, in the description of PCT Kokai publication WO/02/40224, a desired gait has been defined as follows.

a) In a broad sense, a desired gait is a combination of a desired motion trajectory and a desired floor reaction
10   force trajectory thereof in a period of one step or a plurality of steps.

b) In a narrow sense, a desired gait is a combination of a desired motion trajectory and a ZMP trajectory thereof in a period of one step.

15   c) A series of gaits is formed of several gaits that are connected.

In walking, once a vertical position of the body 3 of the robot 1 (a height of the body) is determined by a body height determining technique proposed previously in
20   Japanese Unexamined Patent Application Publication No. 10-86080 by the present applicant, a translational floor reaction force vertical component is subordinately determined. Furthermore, a translational floor reaction force horizontal component is also determined by
25   determining the horizontal body position trajectory of the robot 1 such that the horizontal component of the moment produced about a desired ZMP by a resultant force of the

inertial force and the gravity generated by the motion of a desired gait becomes zero. For this reason, a desired ZMP alone has been adequate as a physical amount to be explicitly set for the floor reaction force of a desired gait in the description of PCT Kokai publication WO/02/40224. Thus, the definition in the above b) has been adequate as the definition of a desired gait in the narrow sense. However, in the running gait of the robot 1 explained in the embodiment (the details will be described hereinafter), a floor reaction force vertical component (a translational floor reaction force vertical component) is also important for control. In the present invention, therefore, a desired trajectory of the floor reaction force vertical component is explicitly set, and then a trajectory of a desired vertical body position or the like of the robot 1 is determined. Hence, in the present description, the following b') will be adopted as the definition of a desired gait in a narrow sense.

b') A desired gait in a narrow sense is a combination of a desired motion trajectory and a desired ZMP trajectory thereof, and a desired translational floor reaction force vertical component trajectory in a one-step period.

In the present description, a desired gait used hereinafter will mean the desired gait in the narrow sense of the above b') unless otherwise specified for the purpose of easy understanding. In this case, "one step" of a desired gait will mean a period from the moment one

leg 2 of the robot 1 touches the ground to the moment the other leg 2 touches the ground. Supplementally, in the embodiment, a desired gait is used to mean a gait for one-step period. This, however, does not have to be

5   necessarily the one-step period; it may alternatively be a period for a plurality of steps or a period that is shorter than one step (e.g., a half step). In the following explanation, "floor reaction force vertical component" will mean "translational floor reaction force

10   vertical component," and the term "moment" will be used for the vertical component (the component about the vertical axis) of a moment of a floor reaction force so as to distinguish it from the "floor reaction force vertical component." Similarly, "floor reaction force horizontal

15   component" will mean "translational floor reaction force horizontal component."

Needless to say, a double stance period in a gait refers to a period during which the robot 1 supports its own weight by the two legs 2, 2. A single stance period

20   refers to a period during which the robot 1 supports its own weight only by one leg 2, and a floating period refers to a period during which both legs 2, 2 are apart from a floor (floating in the air). In the single stance period, the leg 2 not supporting the self-weight of the robot 1 is

25   referred to as a "free leg." The running gait explained in the present embodiment does not have the double stance period, but alternately repeats the single stance period

(landing period) and the floating period. In this case, during the floating period, both legs 2, 2 do not support the self-weight of the robot 1; however, the leg 2 that was a free leg and the leg 2 that was a supporting leg

5   during a single stance period immediately before the floating period will be referred to as a "free leg" and a "supporting leg," respectively, even in the floating period.

Taking the running gait shown in Fig. 5 as an example,

10   an outline of a desired gait generated by the gait generating device 100 will be explained. More definitions and details related to gaits have been given also in Japanese Unexamined Patent Application Publication No. 10-86081 previously proposed by the present applicant, so

15   that the following will mainly give a description not covered by the Japanese Unexamined Patent Application Publication No. 10-86081.

First, the running gait shown in Fig. 5 will be explained. This running gait is a gait similar to a

20   typical human running gait. In this running gait, the single stance period in which the foot 22 of only either the right or left leg 2 (supporting leg) of the robot 1 lands (contacts the ground) and a floating period in which both the legs 2, 2 float in the air are alternately

25   repeated. In Fig. 5, the first state illustrates a state wherein a single stance period has begun (initial stage), the second state illustrates a state of a midpoint of the

single stance period, the third state illustrates a state
wherein a floating period following the single stance
period has begun (an end of the single stance period), the
fourth state illustrates a state of a midpoint of the

5   floating period, and the fifth state illustrates an end of
the floating period (a start of the next single stance
period).

In this running gait, the robot 1 lands at the heel
of the foot 22 of the supporting leg (the leg 2 on the

10   front side in the advancing direction of the robot 1) at
the beginning of the single stance period, as shown in the
first state of Fig. 5. Subsequently, the robot 1 brings
substantially the entire surface of the sole of the landed
foot 22 (the foot 22 of the supporting leg) into contact

15   with the ground as shown in the second state of Fig. 5,
and then kicks the floor with the tiptoe of the foot 22
(the foot 22 of the leg 2 on the rear side with respect to
the advancing direction of the robot 1 in the third state
of Fig. 5) of the supporting leg to jump into the air, as

20   shown in the third state of Fig. 5. This ends the single
stance period and starts the floating period at the same
time. The free leg in the single stance period exists
behind the supporting leg at the beginning of the single
stance period, as shown in the first state of Fig. 5, but

25   swung out to the front of the supporting leg toward the
next predetermined landing position, as shown in the
second and the third states of Fig. 5. Next, following

the floating period shown in the fourth state of Fig. 5,
the robot 1 lands at the heel of the foot 22 of the free
leg (the leg 2 that was the free leg in the single stance
period immediately before the floating period started),
5   and the next single stance period is begun.

Considering the running gait shown in Fig. 5, a basic
outline of a desired gait generated by the gait generating
device 100 will be explained. Although more details will
be discussed later, when the gait generating device 100
10   generates a desired gait, basic required values (required
parameters) for generating the desired gait, such as a
landing position/posture (expected landing
position/posture) of the foot 22 of a free leg and a
landing time (expected landing time), are supplied to the
15   gait generating device 100 according to a required
operation or the like of the joystick 73. The gait
generating device 100 then generates the desired gait
using the required parameters. More detailedly, the gait
generating device 100 determines parameters (referred to
20   as gait parameters) that specify some constituent elements
of the desired gait, such as a desired foot
position/posture trajectory and a desired floor reaction
force vertical component trajectory of the desired gait,
on the basis of the above required parameters, and then
25   sequentially determines instantaneous values of the
desired gait by using the gait parameters so as to
generate a time series pattern of the desired gait.

In this case, a desired foot position/posture trajectory (to be more specific, a desired trajectory of each spatial component (X-axis component or the like) of the position and the posture of a foot) is generated for

5   each foot 22 by using a finite-duration setting filter proposed in Patent No. 3233450 by the present applicant. This finite-duration setting filter includes a plurality of stages (3 stages or more in the present embodiment) of first-order lag filters of variable time constants, that

10   is, filters represented in terms of a transfer function of $1/(1+\tau s)$ (τ is a variable time constant. Hereinafter, the filter will be referred to as a unit filter), the plurality of stages of the filters being connected in series. This arrangement makes it possible to generate

15   and output a trajectory that reaches a specified value at desired specified time. In this case, time constant τ of the unit filter of each stage is always variably set in sequence according to remaining time until the above specified time after starting the generation of an output

20   of the finite-duration setting filter. More specifically, the setting is made such that, the value of τ is decreased from a predetermined initial value (>0) as the remaining time reduces, and the value of τ finally reaches zero at the specified time at which the remaining time reaches

25   zero. A step input of a height based on the specified value (more specifically, a change amount from an initial value to the specified value of an output of the finite-

duration setting filter) is supplied to the finite-duration setting filter. The finite-duration setting filter not only generates an output that reaches a specified value at specified time but also makes it possible to set a changing rate of an output of the finite-duration setting filter at specified time to zero or substantially zero. Especially when three stages or more (3 stages will do) of the unit filter are connected, the changing acceleration (a differential value of a changing rate) of an output of the finite-duration setting filter can be reduced to zero or substantially zero.

The desired foot position/posture trajectory generated by the finite-duration setting filter as described above is the desired position/posture trajectory of each foot 22 on a supporting leg coordinate system, which is fixed on a floor surface and which is to be discussed later.

The desired foot position/posture trajectory generated as described above is generated such that the position of each foot 22 begins moving, while gradually accelerating from the initial in-contact-with-the-ground state (the state at the initial time of a desired gait) toward an expected landing position. Further, the desired foot position/posture trajectory is generated such that the changing rate of the position is gradually decelerated to zero or substantially zero until the expected landing time is finally reached, and the expected landing position

is reached at the expected landing time at which the trajectory comes to its end. Hence, the ground speed at the moment each foot 22 lands becomes zero or substantially zero (the changing rate of the position of each foot 22 on the supporting leg coordinate system secured to a floor). Accordingly, a landing impact will be low even when the robot 1 lands from the state wherein all legs 2, 2 are simultaneously present in the air (the state in the floating period) in a running gait.

In the aforesaid running gait, the vertical velocity of the body 3 switches downward from the latter half of the floating period due to the gravity acting on the robot 1, and remains downward even at the time of landing. Therefore, if the desired foot position/posture trajectory is generated such that the ground speed at the moment each foot 22 lands reaches zero or substantially zero, as described above, and if the desired position/posture trajectory of the body 3 is generated to satisfy a dynamic balance condition, as will be discussed later, then the relative velocity of the foot 22 of a free leg with respect to the body 3 switches upward immediately before landing. This means that, at a landing moment of a running gait, the desired gait of the robot 1 is such that the robot 1 lands while withdrawing the leg 22 that is a free leg toward the body 3. In other words, according to the desired gait in the present embodiment, the robot 1 lands while pulling the foot 22 up, as observed from the

body 3, so that the ground speed of the foot 22 of the free leg reaches zero or substantially zero. This restrains a landing impact to prevent the landing impact from becoming excessive.

5   Furthermore, in the present embodiment, the finite-duration setting filter is composed of three stages of more (e.g., three stages) of the unit filters connected in series, so that the velocity of each foot 22 (the changing rate of a foot position) reaches zero or substantially 10   zero by expected landing time and the acceleration of each foot 22 also reaches zero or substantially zero at the expected landing time when the foot 22 stops. This means that the ground acceleration also becomes zero or substantially zero at the landing instant. Hence, the 15   landing impact will be further restrained. Especially, even if actual landing time of the robot 1 deviates from desired landing time, the impact no longer increases much. Supplementally, the number of stages of the unit filters of the finite-duration setting filter may be two to make 20   setting so that the ground speed of each foot 22 reaches zero or substantially zero at expected landing time. In this case, however, the acceleration of each foot 22 at expected landing time does not usually become zero.

Regarding a foot posture, after each foot 22 lands at 25   its heel at expected landing time, the foot continues to move until substantially the entire sole of the foot 22 comes in contact with a floor. For this reason, the foot

posture trajectory is generated by the finite-duration setting filter, setting the time at which substantially the entire sole of the foot 22 comes in contact with the floor to the above specified time.

5   In the present embodiment, the foot position trajectory has been generated using the finite-duration setting filter. Alternatively, however, a desired foot position trajectory may be generated using a function, such as a polynomial, that is set such that the changing

10   rate of a foot position at expected landing time (a time differential value of a foot position) reaches zero or substantially zero and further the changing acceleration of the foot position at the expected landing time (a time differential value of the changing rate) reaches zero or

15   substantially zero. This applies also to the generation of a desired foot posture trajectory. However, regarding the generation of the desired foot posture trajectory, a function, such as a polynomial, is set such that the changing rate of the posture of each foot 22 and the

20   changing acceleration thereof reaches zero or substantially zero at the time when substantially the entire sole of each foot 22 comes in contact with a floor, as described above.

          A desired floor reaction force vertical component

25   trajectory is set as shown in, for example, Fig. 6. In the present embodiment, the shape of a desired floor reaction force vertical component trajectory in a running

gait (strictly speaking, the shape in a single stance period) is specified to be trapezoidal (a shape projecting to an increasing side of a floor reaction force vertical component). The height of the trapezoid and the time of a bending point are regarded as gait parameters defining a desired floor reaction force vertical component trajectory in determining the gait parameters (floor reaction force vertical component trajectory parameters). In a floating period of a running gait, the desired floor reaction force vertical component is steadily set to zero. As in the case of the present example, a desired floor reaction force vertical component trajectory is preferably set so that it is virtually continuous (so that values are not discontinuous). This is for ensuring smooth operations of joints of the robot 1 when controlling a floor reaction force. The term "virtually continuous" means that a skipped value that inevitably takes place when a trajectory that is continuous in an analog fashion (a continuous trajectory in a true meaning) is digitally expressed by a discrete-time system does not cause the continuity of the trajectory to be lost.

A desired ZMP trajectory is set as follows. In the running gait shown in Fig. 5, as described above, the robot 1 lands at the heel of the foot 22 of a supporting leg, and then kicks at the tiptoe of the foot 22 of the supporting leg to jump into the air. Lastly, the robot 1 lands at the heel of the foot 22 of a free leg, as

described above.   Therefore, as shown in the upper diagram

of Fig. 7, the desired ZMP trajectory in the single stance

period is set such that it takes the heel of the foot 22

of the supporting leg as its initial position, and then

5   extends to the center in the longitudinal direction of the

foot 22 in the period in which substantially the entire

sole of the foot 22 of the supporting leg comes in contact

with the ground, and thereafter, reaches the tiptoe of the

foot 22 of the supporting leg by floor leaving time.   Here,

10   the upper diagram of Fig. 7 shows a desired ZMP trajectory

in an X-axis direction (longitudinal direction), while a

lower diagram of Fig. 7 shows a desired ZMP trajectory in

a Y-axis direction (lateral direction).   The desired ZMP

trajectory in the Y-axis direction in a single stance

15   period is set at the same position as the central position

of an ankle joint of a supporting leg 2 in the Y-axis

direction, as shown in the lower diagram of Fig. 7.

In a running gait, after a single stance period ends,

both legs 2, 2 leave a floor, and the floor reaction force

20   vertical component becomes zero.   When the floor reaction

force vertical component is zero, that is, during a

floating period, the total center of gravity of the robot

1 is subject to free fall motion, and an angular momentum

change about the total center of gravity is zero.   At this

25   time, the moment of a resultant force of gravity and an

inertial force that acts on the robot 1 is zero at an

arbitrary point of a floor, so that a desired ZMP is

indefinite. This means that any point of the floor

satisfies a condition of ZMP represented by "a point of

action at which the horizontal component of the moment, in

which a resultant force of gravity and an inertial force

5   acts, is zero." In other words, setting the desired ZMP

at an arbitrary point satisfies a dynamic balance

condition in that the horizontal component of the moment

in which the above resultant force acts about the desired

ZMP is zero. Hence, the desired ZMP may be set

10   discontinuously. For example, the desired ZMP may be set

so that it does not move from a desired ZMP position when

leaving a floor (when a single stance period ends) in a

floating period, and it moves discontinuously (in steps)

to a desired ZMP position for landing at the end of the

15   floating period. In the present embodiment, however, the

position of the desired ZMP trajectory in the X-axis

direction in a floating period has been set so as to

continuously move to the landing position of the heel of

the foot 22 of a free leg from the tiptoe of the foot 22

20   of a supporting leg by the time the next free leg 2 lands,

as shown in the upper diagram of Fig. 7. Further, as

shown in the lower diagram of Fig. 7, the position of the

desired ZMP trajectory in the Y-axis direction in a

floating period has been set so as to continuously move to

25   the Y-axis directional position of the center of the ankle

joint of a free leg 2 from the Y-axis directional position

of the center of the ankle joint of a supporting leg 2 by

the time the next free leg 2 lands. In other words, the desired ZMP trajectory has been set so that it is continuous (virtually continuous) in all periods of a gait. As it will be discussed hereinafter, a desired gait has

5   been generated so that a moment of the resultant force of gravity and an inertial force (excluding a vertical component) about the desired ZMP becomes zero (to be more specific, a desired body position/posture trajectory has been adjusted). Taking an approximation error into

10   account, the desired ZMP trajectory is desirably set to be continuous (virtually continuous) also in a floating period in order to ensure a smooth generated gait. However, a dynamic model, which is used in the present embodiment and which will be discussed later, makes it

15   possible to uniquely generate a desired gait that sets the horizontal component of a moment about a desired ZMP to zero independently of the position of a desired ZMP. Therefore, the desired ZMP does not have to be always continuous.

20   In the present embodiment, the positions and time of the bending points of the desired ZMP trajectory as shown in Fig. 7 are set as ZMP trajectory parameters (parameters defining the desired ZMP trajectory). The meaning of "virtually continuous" of the aforementioned ZMP

25   trajectory is the same as that in the case of the above floor reaction force vertical component trajectory.

     The ZMP trajectory parameters are determined such

that a high stability margin is secured and no sudden change takes place. Here, a state in which a desired ZMP exists near the center of a least convex polygon (so-called supporting polygon) that includes a ground contact

5   surface of the robot 1 indicates a high stability margin (refer to Japanese Unexamined Patent Application Publication No. 10-86081 for more detail). The desired ZMP trajectory shown in Fig. 7 has been set to meet such a condition.

10   A desired body position/posture, a desired foot position/posture, and a reference body posture, which will be discussed hereinafter, are described in terms of a global coordinate system. The global coordinate system is a coordinate system fixed to a floor. More specifically,

15   a supporting leg coordinate system to be discussed hereinafter is used as the global coordinate system.

In the present embodiment, the gait generating device 100 generates a reference body posture in addition to a desired body posture. The reference body posture is a

20   body posture generated directly on the basis of requests regarding a gait (requests from a unit, such as an action scheduler, or from an external source (the joystick 73 or the like) sent to the gait generating device 100).

A desired body posture (representing hereinafter a

25   desired body posture unless "reference" is added) is generated such that it follows or agrees with a reference body posture in a long term.

In walking, generally, a desired body posture may be always set to agree with a reference body posture as in the case of an embodiment disclosed in the description of PCT Kokai publication WO/02/40224. Although the PCT Kokai publication WO/02/40224 does not refer to the concept of a reference body posture, it explicitly and preferentially gives desired body posture patterns, which is equivalent to steady agreement of desired body postures with reference body postures.

However, in a gait including a floating period, as in running, or walking on a low-friction floor surface, simply adjusting a horizontal body acceleration or the like is not enough to satisfy a dynamic balance condition while maintaining a floor reaction force horizontal component and a floor reaction force vertical component of a desired gait within a permissible range (or within a friction limit) at the same time.

In the present embodiment, therefore, a desired body posture is deliberately deviated from a reference body posture, as necessary. To be more specific, motion modes explained below are generated in a combined manner so as to satisfy the dynamic balance condition while having a floor reaction force horizontal component and a floor reaction force moment vertical component of a desired gait fall within a permissible range (or within a friction limit).

As shown in Fig. 8, when the robot 1 is in a certain

motion state, if only a horizontal body acceleration is perturbated (slightly changed), then a total center-of-gravity horizontal acceleration and an angular momentum about the total center-of-gravity of the robot 1 are

5   perturbated. More specifically, perturbating the horizontal body acceleration perturbates the floor reaction force moment horizontal component about a desired ZMP (a component about the horizontal axis) and the floor reaction force horizontal component without perturbating

10   the floor reaction force vertical component that dynamically balances with a resultant force of an inertial force and gravity of the robot 1 produced by the perturbation of the horizontal body acceleration (without perturbating a total center-of-gravity vertical

15   acceleration of the robot 1). The motion mode that perturbs the horizontal body acceleration of the robot 1 as described above is referred to as a body translational mode.

In other words, a motion in which the floor reaction

20   force moment horizontal component about the desired ZMP and the floor reaction force horizontal component are changed without changing the floor reaction force vertical component is referred to as the body translational mode. In the body translational mode, the floor reaction force

25   moment vertical component (the component about the vertical axis) is also perturbated; however, no attention will be paid to this aspect in this case.

A change in the floor reaction force moment horizontal component per unit acceleration at this time is denoted by ΔMp and a change in the floor reaction force horizontal component per unit acceleration is denoted by

5   ΔFp. If the body 3 is horizontally accelerated forward in the situation illustrated in Fig. 8, then ΔMp and ΔFp act in the directions of the arrows shown in Fig. 8.

To facilitate perceptual understanding, the floor reaction force that balances with the resultant force of

10   an inertial force and gravity generated by a motion has been used for expression. However, it is theoretically more accurate to express using the resultant force of an inertial force and gravity. The above resultant force and the floor reaction force have the same magnitude but

15   opposite directions.

In comparison with the above, if the body inclination angular acceleration (the angular acceleration of the inclination angle of the body 3) is perturbated about a certain point Pr from a certain motion state of the robot

20   1, as shown in Fig. 9, then the angular momentum (excluding the component about the vertical axis) about the total center-of-gravity is perturbated, while the total center-of-gravity of the robot 1 remains unperturbated. This means that perturbating the body

25   inclination angle acceleration about the point Pr perturbates the floor reaction force moment horizontal component about a desired ZMP without perturbating the

floor reaction force vertical component and the floor reaction force horizontal component. The motion mode in which the body inclination angle acceleration of the robot 1 is perturbated as described above is referred to as the body inclination mode.

In other words, the motion in which the floor reaction force moment horizontal component about a desired ZMP is changed without changing a floor reaction force vertical component and a floor reaction force horizontal component is referred to as the body inclination mode.

A change in the floor reaction force moment horizontal component per unit angular acceleration at this time is denoted by ΔMr and a change in the floor reaction force horizontal component per unit angular acceleration is denoted by ΔFr. ΔFr is zero. If an angular acceleration of a body inclination angle is generated to cause the body 3 to lean forward in the situation shown in Fig. 9, then ΔMr acts in the direction of the arrow shown in Fig. 9.

Further, if a body yaw angular acceleration (the rotational angular acceleration about the vertical axis of the body 3) is perturbated about a certain point Pq from a certain motion state of the robot 1, as shown in Fig. 10, then the angular momentum vertical component about the total center of gravity is perturbated, while the total center of gravity of the robot 1 remains unperturbated. Incidentally, if the total center of gravity of the robot

1 is not perturbated, then the perturbation of the angular momentum vertical component does not depend on a point of action. Hence, perturbating the body yaw angular acceleration about the point Pq perturbates the floor

5   reaction force moment vertical component about a desired ZMP without perturbating the floor reaction force vertical component, the floor reaction force horizontal component, and the floor reaction force moment horizontal component. The motion mode in which the body yaw angular acceleration

10   of the robot 1 is perturbated as described above is referred to as the body yaw rotation mode.

In other words, the body motion in which the floor reaction force moment vertical component about a desired ZMP is changed without changing a floor reaction force

15   vertical component, a floor reaction force horizontal component, and a floor reaction force moment horizontal component is called the body yaw rotation mode.

A change in the floor reaction force moment vertical component per unit angular acceleration at this time is

20   denoted by ΔMbz, and a change in the floor reaction force horizontal component per unit angular acceleration is denoted by ΔFb. ΔFb is zero. If the body 3 is rotated in the direction of the arrow at the unit angular acceleration (rotated at an angular acceleration $\beta b=1$) in

25   the situation shown in Fig. 10, then ΔMbz acts in the direction of the arrow shown in Fig. 10.

In the motion shown in Fig. 10, the body 3 has been

rotated so that the positions of the distal ends of both arms 5, 5 remain unchanged as observed from the supporting leg coordinate system (the coordinate system fixed to a floor). However, a motion in which an arm 5 is rotated together with the body 3 without changing the relative position/posture of the arm 5 in relation to the body 3 may be defined as the body yaw rotation mode. In this case, however, a motion equation to be discussed hereinafter has to be slightly changed.

Further, if the distal ends of both arms 5, 5 are perturbated longitudinally in opposite directions from each other from a motion state of the robot 1, as illustrated in Figs. 11 (a) and (b), then the angular momentum vertical component about the total center of gravity is perturbated, while the total center of gravity of the robot 1 remains unperturbated. Hereinafter, this motion mode will be referred to as an antiphase arm swing mode. In other words, the arm swing motion mode in which the floor reaction force moment vertical component about a desired ZMP is perturbated without perturbating a floor reaction force vertical component, a floor reaction force horizontal component, and a floor reaction force moment horizontal component is referred to as the antiphase arm swing mode.

A motion in which a right arm 5R is moved forward by a unit amount and a left arm 5L is moved backward by a unit amount is referred to as an antiphase arm swing of a

unit angle. Figs. 11 (a) and (b) illustrate a state wherein an antiphase arm swing angle is θaz.

A change in the floor reaction force moment vertical component per unit angular acceleration in the antiphase arm swing mode is denoted by ΔMaz, and a change in the floor reaction force horizontal component per unit angular acceleration is denoted by ΔFa. ΔFa is zero. In the situation shown in Figs. 11 (a) and (b), if the right arm 5R is accelerated forward, while the left arm 5L is accelerated backward (swinging at an angular acceleration βa>0), then a floor reaction force moment vertical component Maz acts in the direction of the arrow (a positive direction of the vertical axis) shown in Fig. 11 (a).

A description will now be given of a dynamic model of the robot 1 used in the present embodiment. In the present embodiment, a simplified (approximated) dynamic model shown below is used. However, regarding the dynamic model shown below, a kinematics model (a model representing the structures and dimensions of joints and links, i.e., a model representing a relationship between joint displacements and the positions/postures of links) will be also necessary.

Fig. 12 shows a dynamic model of the robot 1 used in the present embodiment. As illustrated, the dynamic model is a model composed of a total of three mass points, namely, two mass points 2m, 2m corresponding to the legs 2

of the robot 1 and a mass point 3m corresponding to the body 3, and four flywheels FHx, FHy, FHbz, and FHaz having inertias but no mass. The flywheels FHx, FHy, FHbz, and FHaz can be rotated about an X-axis (longitudinal axis), a Y-axis (lateral axis), a Z-axis (vertical axis), and a Z-axis (vertical axis), respectively. This dynamic model is decoupled, that is, the dynamic model is constructed such that the dynamics (the dynamics of the mass points 2m, 2m) of the legs 2, 2, the dynamics of the body 3 (the dynamics of the mass point 3m and the flywheels FHx, FHy and FHbz), and the dynamics of the arms 5, 5 (the dynamics of the flywheel FHaz) do not interfere with each other, and the dynamics of the entire robot 1 is represented by their linear connection. In addition, a relationship between a motion of the body 3 and a floor reaction force is separated into a relationship between a translational motion of the body 3 (body translation mode) and a floor reaction force, a relationship between an inclination motion of the body 3 (body inclination mode) and a floor reaction force, a relationship between a yaw rotational motion of the body 3 (body yaw rotation mode) and a floor reaction force, and a relationship between an antiphase arm swing motion of both arms 5, 5 (antiphase arm swing mode) and a floor reaction force. To be more specific, a floor reaction force generated by a horizontal motion of the body mass point 3m corresponds to a floor reaction force generated by a horizontal translational motion of

the body 3 (body translation mode), and a floor reaction force generated by a rotational motion of the flywheels FHx and FHy corresponds to a floor reaction force generated by a rotational motion of an inclination angle of the body 3 (body inclination mode). The rotational motion of the flywheel FHx corresponds to the rotational motion of an inclination angle of the body 3 in the roll direction (about the X-axis), and the rotational motion of the flywheel FHy corresponds to the rotational motion of an inclination angle of the body 3 in the pitch direction (about the y-axis). A floor reaction force generated by the rotational motion of the flywheel FHbz corresponds to a floor reaction force generated by a yaw rotational motion of the body 3 (the body yaw rotation mode). A floor reaction force generated by the rotational motion of the flywheel FHaz corresponds to a floor reaction force generated by an antiphase arm swing motion (the antiphase arm swing mode).

The mass of the arms of the robot 1 is assumed to be included in the body 3, and the body mass point 3m has a mass that includes the mass of the arms 5, 5.

For the convenience of explanation, variables and parameters related to the dynamic model will be defined as follows. Each of the mass points 2m, 2m and 3m corresponds to a representative point of a part with which it is associated or a point uniquely decided geometrically from the position/posture of the part. For instance, the

position of the mass point 2m of a supporting leg 2 is defined as the point above the aforesaid representative point of the sole of the foot 22 of the leg 2 by a predetermined distance.

5   Zsup: Supporting leg mass point vertical position

Zswg: Free leg mass point vertical position

Zb: Body mass point vertical position (usually different from a vertical body position)

ZGtotal: Overall center-of-gravity vertical position

10   Xsup: Supporting leg mass point X position

Ysup: Supporting leg mass point Y position

Xswg: Free leg mass point X position

Yswg: Free leg mass point Y position

Xb: Body mass point X position (The body mass point

15   position is the position offset by a predetermined distance in the longitudinal direction of the body from the aforesaid point Pr. The offset is determined such that the center-of-gravity position of an exact model and the center-of-gravity position of the present dynamic

20   model agree with each other as much as possible in an upright stance or the like. This is usually different from a horizontal body position.)

Yb: Body mass point Y position

XGtotal: Overall center-of-gravity horizontal X position

25   YGtotal: Overall center-of-gravity horizontal Y position

θbx: Body inclination angle about X-axis relative to vertical direction

$\theta$by: Body inclination angle about Y-axis relative to vertical direction

θbz: Body yaw rotational angle

θaz: Antiphase arm swing angle

5   mb: Body mass point mass

msup: Supporting leg mass point mass

mswg: Free leg mass point mass

mtotal: Total mass of robot (= mb + msup + mswg)

J: Body inertial moment (Equivalent inertial moment in the

10   body inclination mode. In other words, this is an inertial moment of FHx and FHy. Usually, it does not agree with the inertial moment of the body 3 part of the actual robot 1.)

Jbz: Body inertial moment about a vertical axis

15   (Equivalent inertial moment in the body yaw rotation mode. Usually, this does not agree with the inertial moment of the body 3 part of the actual robot 1.)

Jaz: Arm swing inertial moment about a vertical axis (Equivalent inertial moment in antiphase arm swing to

20   cancel a spin. In other words, it is an inertial moment of FHaz.)

Fx: Floor reaction force X component (More specifically, a longitudinal (X-axis) component of a translational floor reaction force)

25   Fy: Floor reaction force Y component (More specifically, a lateral (Y-axis) component of a translational floor reaction force)

Fz: Floor reaction force vertical component (More
specifically, a vertical (Z-axis) component of a
translational floor reaction force.   This is equivalent to
a desired translational floor reaction force vertical
component in the present embodiment.)

Mx: X component of a floor reaction force moment about a
desired ZMP (More specifically, a component about a
longitudinal axis (X-axis) of a floor reaction force
moment)

My: Y component of a floor reaction force moment about a
desired ZMP (More specifically, a component about a
lateral axis (Y-axis) of a floor reaction force moment)

Mz: Z component of a floor reaction force moment about a
desired ZMP (More specifically, a component about a
vertical axis (Z-axis) of a floor reaction force moment)

An X position and a Y position of each of the mass
points 2m and 3m mean a position in the longitudinal
direction (X-axis direction) and a position in the lateral
direction (Y-axis direction), respectively.   In the
present embodiment, a positional relationship between a
position of the mass point 2m of each leg 2 and a position
of the foot 22 of the leg 2 (a position of a predetermined
representative point of the foot 22) is determined in
advance, so that if one of the positions is decided, then
the other position is uniquely decided.   Further, a
positional relationship between the body mass point 3m and
the position of the body 3 (a position of a predetermined

representative point of the body 3) is determined in advance on the basis of a posture angle of the body 3 (hereinafter, regarding the body, a posture angle will mean an inclination angle and a yaw angle), and if a

5   position and a posture angle of one of them are determined, then the position of the other is uniquely determined.

For an arbitrary variable X, dX/dt denotes first order differentiation of X, and d2X/dt2 denotes second order differentiation. Therefore, if the variable X

10   denotes displacement, then dX/dt means velocity and d2X/dt2 means acceleration. g denotes a gravity acceleration constant. Here, g takes a positive value.

A motional equation of the above dynamic model (an equation expressing a dynamic balance condition) is

15   represented by equation 01, equation 02x, equation 02y, equation 03x, equation 03y, and equation 03z.

Fz=mb*(g+d2Zb/dt2)+msup*(g+d2Zsup/dt2)

                        +mswg*(g+d2Zswg/dt2) ...... Equation 01

20

Fx=mb*d2Xb/dt2+msup*d2Xsup/dt2+mswg*d2Xswg/dt2

                                    ...... Equation 02x

Fy=mb*d2Yb/dt2+msup*d2Ysup/dt2+mswg*d2Yswg/dt2

25   ...... Equation 02y

Mx=mb*(Yb-Yzmp)*(g+d2Zb/dt2)

$$-mb*(Zb-Zzmp)*(d2Yb/dt2)$$

$$+msup*(Ysup-Yzmp)*(g+d2Zsup/dt2)$$

$$-msup*(Zsup-Zzmp)*(d2Ysup/dt2)$$

$$+mswg*(Yswg-Yzmp)*(g+d2Zswg/dt2)$$

$$-mswg*(Zswg-Zzmp)*(d2Yswg/dt2)+J*d2\theta bx/dt2$$

...... Equation 03x

$$My=-mb*(Xb-Xzmp)*(g+d2Zb/dt2)$$

$$+mb*(Zb-Zzmp)*(d2Xb/dt2)$$

$$-msup*(Xsup-Xzmp)*(g+d2Zsup/dt2)$$

$$+msup*(Zsup-Zzmp)*(d2Xsup/dt2)$$

$$-mswg*(Xswg-Xzmp)*(g+d2Zswg/dt2)$$

$$+mswg*(Zswg-Zzmp)*(d2Xswg/dt2)+J*d2\theta by/dt2$$

...... Equation 03y

$$Mz=mb*(Xb-Xzmp)*(d2Yb/dt2)-mb*(Yb-Yzmp)*(d2Xb/dt2)$$

$$+msup*(Xsup-Xzmp)*(d2Ysup/dt2)$$

$$-msup*(Ysup-Yzmp)*(d2Xsup/dt2)$$

$$+mswg*(Xswg-Xzmp)*(d2Yswg/dt2)$$

$$-mswg*(Yswg-Yzmp)*(d2Xswg/dt2)$$

$$+Jbz*d2\theta bz/dt2+Jaz*d2\theta az/dt2$$

...... Equation 03z

Furthermore, for a total center-of-gravity position of the robot, the following relational expressions hold:

$$ZGtotal=(mb*Zb+msup*Zsup+mswg*Zswg)/mtotal$$

...... Equation 04

XGtotal=(mb*Xb+msup*Xsup+mswg*Xswg)/mtotal

...... Equation 05x

YGtotal=(mb*Yb+msup*Ysup+mswg*Yswg)/mtotal

...... Equation 05y

The following will show a relationship between the above dynamic model and the above ΔFp, ΔMp, ΔFr, and ΔMr.

The above ΔFp is a perturbation amount of Fx or Fy when d2Xb/dt2 or d2Yb/dt2 is perturbated by a unit amount in equation 02x or equation 02y, so that it is determined according to the following equation:

ΔFp = mb   ... Equation 06

More specifically, the change ΔFp of a floor reaction force horizontal component per unit acceleration in the direction of each horizontal axis (X-axis, Y-axis) in the body translation mode corresponds to the mass of the body mass point 3m of the dynamic model.

The above ΔMp is a perturbation amount of My or Mx when d2Xb/dt2 or d2Yb/dt2 is perturbated by a unit amount in equation 03y or equation 03x, so that it is determined according to the following equation:

ΔMp = mb*(Zb-Zzmp)   ... Equation 07

More specifically, the change ΔMp of a floor reaction force moment horizontal component per unit acceleration in the direction of each horizontal axis (X-axis, Y-axis) in the body translation mode is obtained by multiplying a body mass point mass of the dynamic model by a height

(vertical position) of the body mass point 3m from a desired ZMP. The relationship between the positions of the body mass point 3m and the desired ZMP and the motion of the body mass point 3m corresponds to the behavior of

5   an inverted pendulum obtained when the body mass point 3m is associated with an inverted pendulum mass point and when the desired ZMP is associated with an inverted pendulum supporting point. To be more accurate, ΔMp in the Y-axis direction is obtained by reversing the sign of

10   the right side of equation 07.

The above ΔFr is a perturbation amount of Fx or Fy when d2θby/dt2 is perturbated by a unit amount in equation 02x or equation 02y, so that it is determined according to the following equation:

15       $\Delta Fr = 0$ ... Equation 08

This means that the change ΔFr of a floor reaction force horizontal component per unit acceleration in the direction of each horizontal axis (X-axis, Y-axis) in the body inclination mode is zero.

20   The above ΔMr is a perturbation amount of Mx or My when d2θbx/dt2 or d2θby/dt2 is perturbated by a unit amount in equation 03x or equation 03y, so that it is determined according to the following equation:

$\Delta Mr = J$ ... Equation 09

25   More specifically, the change ΔMr of a floor reaction force moment horizontal component per unit acceleration in the direction of each horizontal axis (X-axis, Y-axis) in

the body inclination mode corresponds to the inertial moments of horizontal axis flywheels (FHx and Fhy).

The above ΔMbz is a perturbation amount of Mz when $d2\theta bz/dt2$ is perturbated by a unit amount in equation 03z,

5 so that it is determined according to the following equation:

$\Delta Mbz = Jbz$ ... Equation 09b

More specifically, the change ΔMbz of a floor reaction force moment component per unit acceleration in

10 the body yaw rotation mode corresponds to the inertial moment of a flywheel FHbz corresponding to body yaw rotation.

The above ΔMaz is a perturbation amount of Mz when $d2\theta az/dt2$ is perturbated by a unit amount in equation 03z,

15 so that it is determined according to the following equation:

$\Delta Maz = Jaz$ ... Equation 09a

More specifically, the change ΔMaz of a floor reaction force moment component per unit angular

20 acceleration of an antiphase arm swing corresponds to the inertial moment of a flywheel FHaz corresponding to an arm swing.

The gait generating device 100 in the present embodiment generates a desired gait for one step in order,

25 the one step for the desired gait (the desired gait in the narrow sense described above) being from the moment one leg 2 of the robot 1 lands to the moment the other leg 2

lands. Hence, for the running gait shown in Fig. 5 to be generated in the present embodiment, a desired gait from the beginning of a single stance period to the end of the following floating period (the beginning of the next

5   single stance period) is generated in sequence. Here, a desired gait that is being newly generated will be referred to as a "current time gait," the next desired gait will be referred to as a "next gait," and a desired gait after next will be referred to as a "next but one

10   time gait." Furthermore, a desired gait generated one step before the "current time gait" will be referred to as a "last time gait."

When the gait generating device 100 newly generates a current time gait, expected positions/postures of landing

15   of the foot 22 of a free leg and required values (requests) of expected landing time for the next two steps of the robot 1 are input as required parameters to the gait generating device 100 (or the gait generating device 100 reads the required parameters from a memory). Then,

20   the gait generating device 100 uses these required parameters to generate a desired body position/posture trajectory, a desired foot position/posture trajectory, a desired ZMP trajectory, a desired floor reaction force vertical component trajectory, a desired arm posture

25   trajectory, etc. At this time, some of the gait parameters specifying these trajectories are corrected, as necessary, to secure continuity of walking.

Taking the generation of the running gait shown in Fig. 5 as an example, gait generation processing of the gait generating device 100 will be explained in detail with reference to Fig. 13 to Fig. 46. Fig. 13 is a flowchart (structured flowchart) illustrating a main routine of the gait generation processing carried out by the gait generating device 100.

First, various initializing operations, including initialization of time t to zero, are performed in S010. This processing is implemented primarily when starting up the gait generating device 100. Next, the processing proceeds to S014 via S012 and waits for a timer interrupt for each control cycle (the calculation processing cycle of the flowchart shown in Fig. 13). The control cycle is denoted by Δt.

Then, the processing proceeds to S016 and determines whether a shift in a gait is taking place. If a shift in the gait is taking place, then the processing proceeds to S018, or if a shift in a gait is not taking place, then it proceeds to S030. Here, "the shift in a gait" means a timing at which the generation of the last time gait has been completed and the generation of the current time gait is about to start. For instance, a control cycle following the control cycle in which the generation of a last time gait has been completed refers to the shift in a gait.

When proceeding to S018, time t is initialized to

zero. The gait generating device 100 then proceeds to
S020 and reads a next time's gait supporting leg
coordinate system, a next but one time's gait supporting
leg coordinate system, a current time gait cycle, and a
next time gait cycle. These supporting leg coordinate
systems and the gait cycles are determined by the above
required parameters. More specifically, in the present
embodiment, the required parameters supplied to the gait
generating device 100 from the joystick 73 or the like
include required values of expected landing
positions/postures (foot positions/postures in a state
wherein the foot 22 has been rotated without slippage such
that its sole is substantially in full contact with a
floor surface after landing) and expected landing time of
the foot 22 of a free leg for up to two steps ahead. The
required value for the first step and the required value
for the second step are supplied to the gait generating
device 100 as the values associated with a current time
gait and a next time gait, respectively, before the
generation of the current time gait is begun (the shift in
a gait in S016 mentioned above). These required values
can be changed in the middle of generating the current
time gait.

Then, the next time's gait supporting leg coordinate
system is determined on the basis of the required value of
the expected landing position/posture of the free leg foot
22 of the first step (the free leg foot 22 in the current

time gait) in the above required parameters.

Referring to, for example, Fig. 16, it is assumed
that the required value for an expected landing
position/posture of the free leg foot 22 (22L in the

5   figure) related to the current time gait (first step)
specifies a position/posture obtained by moving by xnext
and ynext in the X-axis direction (in the longitudinal
direction of a supporting leg foot 22R of the current time
gait) and in the Y-axis direction (in the lateral

10   direction of the supporting leg foot 22R of the current
time gait), respectively, of a current time's gait
supporting leg coordinate system, and by rotating about
the Z-axis (about the vertical axis) by θznext with
respect to a landing position/posture of the supporting

15   leg foot 22 (22R in the figure) of the current time gait.
Here, the supporting leg coordinate system is a global
coordinate system (a coordinate system fixed to a floor)
in which a point, at which a perpendicular line extended
onto a floor surface from the center of the ankle of a

20   supporting leg foot 2 intersects with the floor surface
(this point agreeing with a representative point of the
foot 22 in a state, wherein substantially the entire
surface of the sole of the supporting leg foot 22 is in
contact with the floor surface in the present embodiment),

25   in a state wherein the supporting leg foot 22 is set in a
horizontal posture (more generally, a posture parallel to
the floor surface) and substantially the entire surface of

the sole of the supporting leg foot 22 is in contact (in close contact) with the floor surface, is defined as an origin thereof, and a horizontal plane passing the origin is defined as an XY plane. In this case, the X-axis

5   direction and the Y-axis direction correspond to the longitudinal direction and the lateral direction, respectively, of the supporting leg foot 22. The origin of the supporting leg coordinate system does not have to agree with the representative point of the foot 22 (a

10   point representing the position of the foot 22) in the state wherein substantially the entire surface of the sole of the supporting leg foot 22 is in contact with the floor surface. Alternatively, the origin may be set at a point on the floor surface that is different from the

15   representative point.

At this time, the next time's gait supporting leg coordinate system is a coordinate system that takes, as its origin, the representative point (more specifically, a point on a floor that agrees with the representative

20   point) of the foot 22L in a case where the foot 22 is landed according to a required value of the expected landing position/posture of the free leg foot 22L of the current time gait as illustrated (in a case where the representative point of the foot 22 is made to agree with

25   the required value of an expected landing position and the posture (orientation) of the foot 22 is made to agree with the required value of an expected landing posture). The

longitudinal direction and the lateral direction of the foot 22L in the horizontal plane passing the origin correspond to an X'-axis direction and Y'-axis direction, respectively.

5   In the same manner described above, a next but one time's gait supporting leg coordinate system (refer to the X" Y" coordinates shown in Fig. 16) is determined on the basis of the required values for the expected landing position/posture of the free leg foot 22 of the second

10   step. A current time gait cycle is determined as the duration from the expected landing time (required value) of the supporting leg foot 22 of the current time gait to the expected landing time (required value) of the free leg foot 22 of the first step (current time gait). The next

15   time gait cycle is determined as the duration from the expected landing time (required value) of the free leg foot 22 of the first step to the expected landing time (required value) of the free leg foot 22 of the second step.

20   The required parameters are input to the gait generating device 100 by necessary operation of the joystick 73 in the present embodiment. Alternatively, however, the required parameters or the positions/postures and gait cycles of the aforesaid supporting leg coordinate

25   systems associated with the required parameters may be stored in advance as a travel schedule of the robot 1. Alternatively, the aforesaid next time and the next but

one time's gait supporting leg coordinate systems and the current time and the next time gait cycles may be determined on the basis of commands (requests) from a manipulation device, such as the joystick 73, and a travel

5   history of the robot 1 up to that moment.

Subsequently, the processing proceeds to S022 wherein the gait generating device 100 determines gait parameters of a normal turning gait as a virtual cyclic gait that follows the current time gait. The gait parameters

10   include a foot trajectory parameter defining a desired foot position/posture trajectory, a reference body posture trajectory parameter defining a body posture trajectory to be based on, a reference arm posture trajectory parameter defining an arm posture trajectory to be based on, a ZMP

15   trajectory parameter defining a desired ZMP trajectory, and a floor reaction force vertical component trajectory parameter defining a desired floor reaction force vertical component trajectory in the normal turning gait. Furthermore, parameters that define a floor reaction force

20   horizontal component permissible range and a floor reaction force moment vertical component permissible range are also included in gait parameters.

In the present description, "the normal turning gait" is used to mean a cyclic gait that does not cause

25   discontinuity in motional states (states of foot position/posture, body position/posture, etc.) of the robot 1 in a boundary of gait when the gait is repeated

(the boundary of a gait for each step in the present embodiment). Hereinafter, "the normal turning gait" may be abbreviated as "the normal gait."

According to the present embodiment, the normal turning gait, which is a cyclic gait, may be defined as follows. A gait for two steps of the robot 1, i.e., a gait composed of a first turning gait following a current time gait and a second turning gait following the first turning gait, is defined as the gait for one cycle of the normal turning gait, and the normal turning gait consists of a repetition of the gait for one cycle. The term "turning" is used here, because it would mean straight advancement when the turning rate is set to zero, and straight advancement can be also included in turning in a broad sense. If a desired gait to be generated is the running gait shown in Fig. 5, then a current time gait of the desired gait is a running gait that has a single stance period and a floating period. Hence, the first turning gait and the second turning gait of the normal turning gait are both gaits that also have a single stance period and a floating period, as in the current time gait. In other words, a basic gait form of the first turning gait and the second turning gait is the same as that of the current time gait.

Supplemental explanation of the normal turning gait will be added. In a bipedal mobile robot, the normal turning gait for one cycle requires gaits in the aforesaid

narrow sense for at least two steps. It is further possible to set a complicated normal turning gait composed of gaits of three steps or more as the gaits for one cycle. The normal turning gait, however, is used only to

5   determine a divergent component (to be discussed in detail hereinafter) at the end (finish time) of the current time gait. Therefore, using the normal turning gait composed of the gaits of three or more steps for one cycle will provide less effect, while the complicated processing for

10   generating the gait is involved. For this reason, the gaits for one cycle in the normal turning gait in the present embodiment include gaits for two steps (the first and the second turning gaits). For a legged mobile robot having three or more feet, the number of gaits for

15   defining the normal turning gait will increase accordingly. In the following description, for the convenience of explanation, the normal turning gait composed of a plurality of gaits in the narrow sense (the gaits for two steps in the present embodiment) will be regarded as the

20   gait of one step.

      A normal turning gait is prepared for provisional use by the gait generating device 100 to determine motional states of the robot 1, including a divergent component or a vertical body position/velocity, and a body posture

25   angle and an angular velocity thereof at the end of a current time gait; it is not directly output from the gait generating device 100.

The term "divergence" means that the position of the
body 3 of the bipedal mobile robot 1 is undesirably
shifted to a position away from the positions of both feet
22 and 22, as shown in Fig. 14. The value of a divergent
5   component is a numeral value indicating how far the
position of the body 3 of the bipedal mobile robot 1 is
away from the positions of both feet 22 and 22 (to be more
specific, the origin of a global coordinate system (a
supporting leg coordinate system) set on the surface with
10   which a supporting leg foot 22 is in contact).

In the present embodiment, gaits are generated using
a divergent component as an indicator so that a desired
gait can be continuously generated without causing the
divergence. However, even if it is an initial divergent
15   component (divergent component at initial time of the
normal turning gait) of a normal gait, which is a typical
example of a continuous gait (a cyclic gait that permits
repetition of a gait of the same pattern without causing
discontinuity of a gait trajectory, and that does not
20   theoretically diverge after an infinite number of
repetitions), the initial divergent component is not
simply zero. The initial divergent component changes if a
parameter of a normal gait changes. In other words, a
proper divergent component changes according to a gait
25   form, such as the manner of walking or the manner of
running, or the like. In the present embodiment,
therefore, a normal gait following a current time gait to

be generated is set on the basis of required parameters

involved in the current time gait, and the initial

divergent component of the normal gait is determined, and

then a current time gait is generated such that the

5   divergent component at the end of the current time gait

agrees with the initial divergent component of the normal

gait (more generally, the current time gait is made to

continue or approximate to the normal gait). The basic

guideline for generating such gaits is the same as that

10   disclosed in PCT Kokai publication WO/02/40224 previously

proposed by the present applicant.

The embodiment of the present invention does not use

a linear dynamic model with three mass points used in the

first embodiment of PCT Kokai publication WO/02/40224.

15   Nevertheless, the concept of the divergent component and

the convergent component defined by the equation given

below can be applied with adequate approximate accuracy to

a perturbation of a behavior of a nonlinear dynamic model

such as the one shown in Fig. 12.

20   Divergent component = Body mass point horizontal

position + Body mass point horizontal velocity / $\omega 0$

... Equation 10

Convergent component = Body mass point horizontal

position - Body mass point horizontal velocity / $\omega 0'$

25   ... Equation 11

where the body mass point horizontal position in this

case indicates a body mass point horizontal position Xb in

the dynamic model shown in Fig. 12.

$\omega 0$ and $\omega 0'$ take predetermined values. The values of
these $\omega 0$ and $\omega 0'$ are substantially the same, although they
do not exactly coincide. Further, the values for
generating walking gaits in PCT Kokai publication
WO/02/40224 must be slightly changed for running.

More details of the divergent component and the
convergent component have been given in PCT Kokai
publication WO/02/40224, so that no more description will
be given here.

In the present embodiment, in addition to the method
disclosed in PCT Kokai publication WO/02/40224, a gait
parameter defining a desired floor reaction force vertical
component trajectory is set, and a total center-of-gravity
vertical position of the robot 1 is determined so as to
dynamically satisfy the desired floor reaction force
vertical component, as will be discussed hereinafter. In
this case, a second order integrated value of the floor
reaction force vertical component will define the total
center-of-gravity vertical position of the robot 1. Hence,
if the desired floor reaction force vertical component is
improperly set, then the total center-of-gravity vertical
position or the vertical body position of the robot 1 will
be too high or too low. Therefore, the method for setting
a desired floor reaction force vertical component is also
an important issue. However, the relationship between a
floor reaction force vertical component and a vertical

body position is similar to the relationship between ZMP and a horizontal body position, so that a technique for determining a desired ZMP for setting a proper horizontal body position/velocity can be applied to the technique for

5   determining a desired floor reaction force vertical component for setting a proper vertical body position/velocity simply by slightly changing a part thereof, as shown in the following present embodiment.

Returning to the main subject, in S022, the

10   processing below is carried out according to the flowchart shown in Fig. 15.

First, in S100, a foot trajectory parameter among the gait parameters of a normal gait is determined to provide a foot position/posture trajectory composed of a current

15   time gait, a first turning gait, and a second turning gait in succession in this order. The following will explain a specific setting method with reference to Fig. 16. In the following explanation, the foot 22 of a supporting leg 2 will be referred to as the supporting leg foot and the

20   foot 22 of a free leg 2 will be referred to as the free leg foot. Further, "start" and "end" will mean start time and end time of a gait or instantaneous gaits at the start time and the end time.

The foot trajectory parameter is constructed

25   primarily of the positions/postures of a supporting leg foot and a free leg foot, respectively, at the start and the end, respectively, of a first turning gait and a

second turning gait, and a gait cycle of each turning gait. In the foot trajectory parameter, the free leg foot position/posture at the start of the first turning gait is defined as the supporting leg foot position/posture at the

5   end of a current time gait observed from a next time's gait supporting leg coordinate system. In this case, in a running gait, the supporting leg foot 22 at the end of the current time gait is moving in the air. And the supporting leg foot position/posture at the end of the

10   current time gait is determined by generating a required value of an expected landing position/posture of the free leg foot 22 of a second step in the required parameter (a required value of an expected landing position/posture in a next time gait of the supporting leg foot 22 of the

15   current time gait) or a foot position/posture trajectory for reaching a free leg position/posture at the end of the next time gait determined on the basis of a next but one time's gait supporting leg coordinate system that corresponds to the above required value (more specifically,

20   the trajectory observed from a next time's gait supporting leg coordinate system) from the supporting leg foot position/posture at the start of the current time gait (= the free leg foot position/posture at the end of the last time gait) by using the finite-duration setting filter

25   until the end of the current time gait.

      The free leg foot position/posture at the end of the next time gait is determined such that the

position/posture of the foot, which is obtained when the foot 22 is turned from that position/posture by a predetermined angle in the pitch direction until it reaches a horizontal posture by lowering its tiptoe while holding the foot 22 in contact with the ground, agrees with the position/posture in the next but one time's gait supporting leg coordinate system. In other words, the free leg foot position/posture at the end of the next time gait is the position/posture of the foot 22 in a state wherein the foot 22 has been turned, from a required value of the landing position/posture of the free leg foot 22 of the second step in the required parameter, by a predetermined angle in the pitch direction by lifting its tiptoe while holding the foot 22 in contact with the ground so that it does not slip (a state wherein the heel has been landed with the tiptoe raised).

Further, the supporting leg foot position/posture at the start of the first turning gait is defined as the free leg foot position/posture at the end of the current time gait observed from the next time's gait supporting leg coordinate system. In this case, the free leg foot position/posture at the end of the current time gait is determined on the basis of the above next time's gait supporting leg coordinate system or a required value of an expected landing position/posture of the free leg of the first step (the current time gait) of the required parameter corresponding thereto, as in the case of the

free leg foot position/posture at the end of the next time
gait. In other words, the free leg foot position/posture
at the end of the current time gait is determined such
that a representative point of the foot, which is obtained
5   when substantially entire surface of the sole of the foot
22 is brought into contact with a floor surface by turning
the foot 22 from the position/posture so as to lower its
tiptoe while holding the foot 22 in contact with the
ground, agrees with the origin of the next time's gait
10   supporting leg coordinate system.

The free leg foot position/posture at the end of the
first turning gait is determined on the basis of a
position/posture on the next but one time's gait
supporting leg coordinate system observed from the next
15   time's gait supporting leg coordinate system, as with the
technique for determining the free leg foot
position/posture at the end of the current time gait or
the free leg foot position/posture at the end of the next
time gait. To be more specific, the free leg foot
20   position/posture at the end of the first turning gait is
set such that the position/posture of the foot, which is
obtained when the foot 22 is turned from that
position/posture by a predetermined angle until it reaches
a horizontal posture while avoiding a slippage and while
25   holding the foot 22 in contact with the ground, agrees
with the position/posture in the next but one time's gait
supporting leg coordinate system as observed from the next

time's gait supporting leg coordinate system.

At the end of the first turning gait, the supporting leg foot 22 is in the air, being off the floor. To determine the trajectory after the supporting leg foot 22

5 leaves the floor, an expected landing position/posture of the supporting leg foot of the first turning gait is set. The expected landing position/posture of the supporting leg foot of the first turning gait is set on the basis of a position/posture on a next but two time gait supporting

10 leg coordinate system observed from the next time's gait supporting leg coordinate system. To be more specific, the expected landing position/posture of the supporting leg foot of the first turning gait is the position/posture on the next but two time gait supporting leg coordinate

15 system observed from the next time's gait supporting leg coordinate system. The next but two time gait supporting leg coordinate system is set such that the relative position/posture relationship between the next but one time's gait supporting leg coordinate system and the next

20 but two time gait supporting leg coordinate system agrees with the relative position/posture relationship between the current time's gait supporting leg coordinate system and the next time's gait supporting leg coordinate system.

The supporting leg foot position/posture at the end

25 of the first turning gait is determined by generating a foot position/posture trajectory for reaching the expected landing position/posture of the supporting leg foot of the

first turning gait from the supporting leg foot position/posture at the start of the first turning gait (more specifically, the trajectory observed from a next time's gait supporting leg coordinate system) by using the finite-duration setting filter until the end of the first turning gait, as in the case where the supporting leg foot position/posture at the start of the first turning gait is determined.

The free leg foot position/posture at the start of the second turning gait is regarded as the supporting leg foot position/posture at the end of the first turning gait observed from the next but one time's gait supporting leg coordinate system. The supporting leg foot position/posture at the start of the second turning gait is regarded as the free leg foot position/posture at the end of the first turning gait observed from the next but one time's gait supporting leg coordinate system.

The free leg foot position/posture at the end of the second turning gait is regarded as the free leg foot position/posture at the end of the current time gait observed from the current time's gait supporting leg coordinate system. The supporting leg foot position/posture at the end of the second turning gait is regarded as the supporting leg foot position/posture at the end of the current time gait observed from the current time's gait supporting leg coordinate system.

The gait cycles of the first turning gait and the

second turning gait are set to be identical to a next time gait cycle. These gait cycles of the first turning gait and the second turning gait do not have to be the same with each other; however, both cycles are preferably

5   determined on the basis of at least a next time gait cycle. Motion parameters (including a time parameter, such as double stance period duration) other than the current time gait, the first turning gait, and the second turning gait are determined, as necessary, so as to satisfy gait

10   conditions (such as an actuator velocity falling within a permissible range, a movable angle being not exceeded, and no interference with a floor or the like) on the basis of the parameters determined above.

 Next, the processing proceeds to S102 and determines

15   a reference body posture trajectory parameter that defines the reference body posture trajectory to be followed by a desired body posture. The reference body posture does not have to be constant as long as it is set to ensure connection at the start (the start of the first turning

20   gait) and the end (the end of the second turning gait) of a normal gait (to ensure that the posture angle of the reference body posture and the angular velocity thereof at the start of a normal gait agrees with those at the end of the normal gait). In the present embodiment, however, for

25   the purpose of easy understanding, a posture related to an inclination angle (an inclination angle relative to the vertical direction) in the reference body posture is set

to an upright posture (vertical posture). This means that, in the present embodiment, the reference body posture related to an inclination angle of the body 3 is set to the upright posture in all periods of the normal gait.

5   Accordingly, in the present embodiment, the angular velocity and angular acceleration of an inclination angle of the reference body posture is zero. A yaw angle trajectory (hereinafter referred to also as a reference yaw angle trajectory) θbz of the reference body posture

10   may be, for example, a motion at a constant angular velocity (an average turning velocity of a normal gait), or may take a sinusoidal wave shape, as in the example (Fig. 18) of a reference antiphase arm swing trajectory, which will be discussed hereinafter. However, the yaw

15   angle trajectory is to be set such that a reference yaw angle and its angular velocity are in succession when the normal gait is repeated.

In the present embodiment, the yaw angle trajectory (hereinafter referred to also as a desired yaw angle

20   trajectory) of a desired body posture is set to agree with a reference yaw angle trajectory.

Subsequently, the processing proceeds to S104 to determine reference arm posture trajectory parameters. To be more specific, parameters related to a total center-of-

25   gravity position of both arms 5, 5 (a relative center-of-gravity position with respect to the body 3), a lateral interval between right and left hands (the distal ends of

both arms 5, 5), and an antiphase arm swing angle are determined. For turning, for example, to the left as shown in Fig. 17, the reference antiphase arm swing angle may be set as shown in Fig. 18. As illustrated in Fig. 18,

5   a reference antiphase arm swing angle θazref is set such that, when a normal gait is repeated, an antiphase arm swing angle and an angular velocity will be both continuous at a boundary of gaits (the boundary between the end of a second turning gait and the next first

10   turning gait) and the relative relationship between the supporting leg and an antiphase arm swing angle at the start of the first turning gait agrees with the relative relationship between the supporting leg and an antiphase arm swing angle at the start of the next first turning

15   gait. In other words, the antiphase arm swing angular velocity at the start of the first turning gait and the antiphase arm swing angular velocity at the end of the second turning gait agree with each other, and the antiphase arm swing angle at the end of the second turning

20   gait is set to a value obtained by adding the antiphase arm swing angle at the start of the first turning gait to the turning angle of the normal gait (the sum of the turning angles of the first turning gait and the second turning gait). In Fig. 18, the reference antiphase arm

25   swing angle θazref has the sinusoidal waveform; however, it may alternatively be set to a constant angular velocity, or it may take an average value of a supporting leg yaw

angle and a free leg yaw angle.

In the present embodiment, the total center-of-gravity positions of both arms 5, 5 of the desired arm posture (the relative position with respective to the body 3) are set to be maintained constant with respect to the body 3.

Next, the processing proceeds to S106 and sets a floor reaction force vertical component trajectory parameter. In this case, the floor reaction force vertical component trajectory parameter is set such that the floor reaction force vertical component trajectory defined by the parameter is virtually continuous (values do not jump in steps), as shown in Fig. 6, in both the first turning gait and the second turning gait. In other words, a desired floor reaction force vertical component trajectory of the normal turning gait is set to have the pattern shown in Fig. 19. According to the pattern, for both the first turning gait and the second turning gait, the floor reaction force vertical component exhibits a trapezoidal change in a single stance period, and the floor reaction force vertical component is maintained at zero in a floating period. The time of break points of the pattern and the height of a trapezoid (peak value) are set as the floor reaction force vertical component trajectory parameters.

When setting the floor reaction force vertical component trajectory parameters, an average value

throughout a gait period of the floor reaction force vertical component (the period equivalent to the sum of the periods of the first turning gait and the second turning gait, that is, the period equivalent to one cycle of a normal gait) is made to agree with the self weight of the robot 1. This means that the average value of the floor reaction force vertical component is set so that it provides the same magnitude as that of the gravity acting on the robot 1 but in an opposite direction.

Setting the floor reaction force vertical component trajectory as described above is necessary to satisfy a normal gait condition. The normal gait conditions is such that a beginning state (a beginning state of a first turning gait) of any state variables (a position, a posture, a velocity, etc. of each part of the robot 1) of a gait observed from a supporting leg coordinate system (a coordinate system set on a plane with which the supporting leg foot 22 is in contact) and a terminal state (a terminal state of a second turning gait) of a gait observed from the next supporting leg coordinate system (the supporting leg coordinate system of the next first turning gait) agree with each other (hereinafter, this condition may be referred to as a boundary condition of a normal gait). Therefore, the difference between a total center-of-gravity vertical velocity of the robot 1 at the end of the normal gait and a total center-of-gravity vertical velocity at the start of the normal gait (more

specifically, the difference between the total center-of-gravity vertical velocity at the end of a second turning gait and the total center-of-gravity vertical velocity at the start of the first turning gait) must be also zero.

5 The difference is an integrated value of the difference between the floor reaction force vertical component and gravity (first-order integrated value); therefore, the floor reaction force vertical component trajectory must be set as described above in order to set the difference to

10 zero.

In the present embodiment, the average value of the floor reaction force vertical component in the period of each of the first turning gait and the second turning gait has been made to agree with the self weight of the robot 1.

15 More specifically, the time of the break points of the trapezoidal portions of the floor reaction force vertical component trajectory in each turning gait has been set based on, for example, the gait cycle of the first turning gait and the second turning gait, and then the heights of

20 the trapezoidal portions have been determined such that the average value of the floor reaction force vertical component in the period of each of the first turning gait and the second turning gait agrees with the self weight of the robot 1 (the heights of the trapezoids are determined

25 by solving an equation representing the condition under which the average value and the self weight coincide, taking the heights of the trapezoids as unknown numbers).

Thus, the difference between the total center-of-gravity vertical velocity at the end of the first turning gait and the total center-of-gravity vertical velocity at the start of the first turning gait will be zero, and the difference between the total center-of-gravity vertical velocity at the end of the second turning gait and the total center-of-gravity vertical velocity at the start of the second turning gait will be also zero. This, however, is not a must. If, for instance, a vertical body position becomes excessively high or low at about a boundary of the first turning gait and the second turning gait, leading to a likelihood of an unreasonable posture, then the heights or the like of trapezoids of the floor reaction force vertical component trajectory of each turning gait may be corrected in the state in which the average value and the self weight agree in each turning gait.

Next, the processing proceeds to S108 to set a permissible range of a floor reaction force horizontal component [Fxmin, Fxmax] (more specifically, a parameter defining it), as shown in Fig. 20, on the basis of the floor reaction force vertical component trajectory set as shown in Fig. 19, as described above. The polygonal line on the negative side in Fig. 20 indicates the permissible lower limit value Fxmin of the floor reaction force horizontal component, while the polygonal line on the positive side indicates the permissible upper limit value Fxmax of the floor reaction force horizontal component. A

supplemental description will be given of a method for setting them. The following will explain a case where a floor surface is horizontal.

The floor reaction force horizontal component is generated from friction between a floor and a foot 22. The friction cannot be generated limitlessly; it has a limit. Hence, the floor reaction force horizontal component of a desired gait has to be always within a friction limit in order to prevent the robot 1 from slipping when the actual robot 1 moves according to a generated desired gait. To meet this condition, a permissible range of the floor reaction force horizontal component will be set, and a desired gait will be generated such that the floor reaction force horizontal component of the desired gait falls within the permissible range, as it will be discussed hereinafter.

When the coefficient of friction between the floor and the foot 22 is denoted by μ, Fxmin must be always set to be not less than $-\mu$ * floor reaction force vertical component, and Fxmax must be set to be not more than μ * floor reaction force vertical component. A simplest setting method is to set them according to the following expression, in which ka is a positive constant that is smaller than 1.

Fxmin = -ka * μ * Floor reaction force vertical component

Fxmax = ka * μ * Floor reaction force vertical component

... Equation 12

The permissible range of the floor reaction force horizontal component shown in Fig. 20 is an example set according to Equation 12. The values and time at the break points of the trapezoidal waveforms or the like in

5   Fig. 20 may be set as the parameters for defining the permissible range of the floor reaction force horizontal component. Alternatively, however, if the permissible range of the floor reaction force horizontal component is determined according to Equation 12, then the value of

10   (ka*μ) in Equation 12 may be simply set as a parameter.

As long as the above condition (the condition in that the floor reaction force horizontal component of a desired gait always falls within a frictional limit) is satisfied, a different setting method may be used to set the

15   permissible range of the floor reaction force horizontal component.

The sequence then proceeds to S109 and sets the permissible range [Mzmin, Mzmax] (more specifically, a parameter defining it) of a floor reaction force moment

20   vertical component, as shown in Fig. 21, on the basis of the floor reaction force vertical component trajectory or the like set as shown in Fig. 19, as described above. The polygonal line on the negative side in Fig. 21 indicates the permissible lower limit value Mzmin of the floor

25   reaction force moment vertical component, while the polygonal line on the positive side indicates the permissible upper limit value Mzmax of the floor reaction

force moment vertical component. A supplemental
description will be given of a method for setting them.
The following will explain a case where a floor surface is
horizontal.

5   The floor reaction force moment vertical component is
generated from friction between a floor and a foot 22.
The friction cannot be generated limitlessly; it has a
limit. Hence, the floor reaction force moment vertical
component of a desired gait has to be always within a
10   friction limit in order to prevent the robot 1 from
spinning when the actual robot 1 moves according to a
generated desired gait. To meet this condition, a
permissible range of the floor reaction force moment
vertical component will be set, and a desired gait will be
15   generated such that the floor reaction force moment
vertical component of the desired gait falls within the
permissible range, as it will be discussed hereinafter.

        If the coefficient of friction between the floor and
the foot 22 is denoted by μ, and an effective radius of
20   the surface of contact between the floor and the foot 22
to generate a moment vertical component (or a square root
of a sectional secondary moment about a desired ZMP of the
surface of contact between the floor and the foot 22) is
denote by r, then Mzmin must be always set to be not less
25   than $-\mu * r *$ floor reaction force vertical component, and
Mzmax must be set to be not more than $\mu * r *$ floor
reaction force vertical component. A simplest setting

method is to set them according to the following expression, in which ka is a positive constant that is smaller than 1.

Mzxmin = -ka $*$ μ $*$ r $*$ Floor reaction force vertical

5   component

Mzmax = ka $*$ μ $*$ r $*$ Floor reaction force vertical

component

                                                        ... Equation 1012

     The permissible range of the floor reaction force

10   moment vertical component shown in Fig. 21 is an example

set according to Equation 1012. The values and time at

the break points of the trapezoidal waveforms or the like

in Fig. 21 may be set as the parameters for defining the

permissible range of the floor reaction force moment

15   vertical component. Alternatively, however, if the

permissible range of the floor reaction force moment

vertical component is determined according to Equation

1012, then the value of (ka$*$$\mu$) in Equation 1012 may be

simply set as a parameter. r is desirably calculated from

20   a desired ZMP and a contact surface at each instant;

alternately, however, r may be a constant.

     As long as the above condition (the condition in that

the floor reaction force moment vertical component of a

desired gait always falls within a frictional limit) is

25   satisfied, a different setting method may be used to set

the permissible range of the floor reaction force moment

vertical component.

Further alternatively, a permissible range may be set by combining a floor reaction force horizontal component and a floor reaction force vertical component moment rather than independently setting the permissible range of a floor reaction force horizontal component and the permissible range of a floor reaction force moment vertical component. This is because the permissible range of a floor reaction force moment vertical component becomes narrower as a floor reaction force horizontal component increases, while the permissible range of the floor reaction force horizontal component becomes narrower as the floor reaction force moment vertical component increases.

Next, the processing proceeds to S110 and sets ZMP trajectory parameters defining the ZMP trajectory of the normal gait that combines the first turning gait and the second turning gait. In this case, a desired ZMP trajectory is set so as to exhibit a high stability margin and no sudden changes, as described above.

To be more specific, according to the running gait shown in Fig. 5, a few moments after the heel of the supporting leg foot 22 lands, substantially the entire surface of the sole of the supporting leg foot 22 comes in contact with the ground, and then, following a few moments, only the tiptoe of the supporting leg foot 22 comes in contact with the ground. Thereafter, the robot 1 kicks the ground with the tiptoe of the supporting leg foot 22

to jump into the air. Lastly, the robot 1 lands at the
heel of the free leg foot 22. The desired ZMP has to
exist within a ground contact plane. In the present
embodiment, therefore, the position of the desired ZMP in
5   the X-axis direction for the first turning gait and the
second turning gait of the normal gait is set so that it
takes the heel of the supporting leg foot 22 as its
initial position and stays at this position until
substantially the entire sole of the foot 22 comes in
10   contact with the ground, as illustrated in the upper
diagram of Fig. 7 described above. Subsequently, the
desired ZMP is set so that it moves to the center of the
supporting leg foot 22, and then moves to the tiptoe by
the time the tiptoe of the foot 22 comes in contact with
15   the ground and remains thereafter at the tiptoe of the
supporting leg foot 22 until the foot 22 leaves the floor.
After that, the desired ZMP is set such that the desired
ZMP continuously moves from the tiptoe of the supporting
leg foot 22 to the landing position of the heel of the
20   free leg foot 22 by the time the next free leg foot 22
lands, as previously described. Thus, the desired ZMP
trajectory (the trajectory in the X-axis direction) of the
normal gait composed of the first turning gait and the
second turning gait will be as illustrated in Fig. 22.
25   The time and positions of the break points of the desired
ZMP trajectory are set as the ZMP trajectory parameters.
In this case, the time of the break points is set on the

basis of gait cycles of the first turning gait and the second turning gait determined based on the required parameters. The positions of the break points are set on the basis of the positions/postures on the next time's gait supporting leg coordinate system and the next but one time's gait supporting leg coordinate system or on the basis of the required values of the expected free leg foot landing positions/postures of the first step and the second step of the required parameters that define these coordinate systems. The position of the ZMP trajectory in the Y-axis direction is set in the same manner as that illustrated in the lower diagram of Fig. 7. More specifically, the trajectory of the positions of the desired ZMP in the Y-axis direction in the first turning gait is set according to the same pattern as that shown in the lower diagram of Fig. 7. The trajectory of the positions of the desired ZMP in the Y-axis direction in the second turning gait is set to have the same shape as that for the first turning gait and connects to the end of the trajectory.

Subsequently, the processing proceeds to S112 and redefines the start time, the end time, and duration of one step (one cycle) of the normal gait as follows.

A normal gait must be a gait in which state variables continuously connect at the start and the end thereof. To easily determine such a gait, in the present embodiment, the start, the end, and the duration of one step of a

normal gait are determined as illustrated in Fig. 19 for convenience sake, which is different from the definition of a gait in the narrow sense described above. Specifically, in the latter half of a single stance period of the first turning gait, the time at which the floor reaction force vertical component has reduced to a certain degree is set as start time Ts of the normal gait. The start time Ts is preferably set to the time of the moment at which the state wherein substantially the entire surface of the sole of the supporting leg foot 22 is in contact with the ground is switched to tiptoe contact with the ground or at the time immediately preceding it, as shown in Fig. 7 (the time when the period of the entire sole surface in contact with the ground ends or the time immediately preceding it, as shown in Fig. 7). A description will now be given of the relationship between the desired ZMP and time Ts shown in Fig. 22 (or Fig. 7) set in S110. After substantially the entire surface of the sole of the supporting leg foot 22 comes in contact with the ground in the first turning gait, the desired ZMP moves to the center of the supporting leg foot 22. The instant the movement to the tiptoe is completed by the tiptoe contact with the ground is established is preferably time Ts. The start time Ts is set on the basis of, for example, the desired ZMP trajectory parameters previously set. The reason for setting the start time Ts as described above will be discussed hereinafter.

As shown in Fig. 19, a cycle Tcyc of the normal gait is a sum of the gait cycles of the first turning gait and the second turning gait. The end time of the normal gait is denoted by Te. Te is set to the time obtained by adding Tcyc to Ts.

The definition of the start, the end, or the like of a gait will be returned to the definition of the gait in the aforesaid narrow sense again from the moment the normal gait is determined (the moment the sequence leaves the loop of S204 shown in Fig. 23). In the following explanation, the start time (the time at which the supporting leg foot 22 lands first) according to the definition of a gait based on the aforesaid narrow sense will be set to 0, and the above start time Ts used until the normal gait is determined will be distinguished from the original start time 0 by using the reference mark Ts (abbreviated to "Ts" in some cases).

Lastly, the processing proceeds to S114 and sets a body posture angle and antiphase arm swing angle restoring period [Tm, Ts2] and [Tm2, Te] of the normal gait. Supplementally, when the normal gait is repeated, the body posture angle and the antiphase arm swing angle should be continuous in a boundary of gaits. For this purpose, the beginning body posture angular velocity and the ending body posture angular velocity of the normal gait must agree with each other, and the beginning antiphase arm swing angular velocity and the ending antiphase arm swing

angular velocity must agree with each other. The

aforesaid period is the period for adjusting a body

posture angle trajectory and an antiphase arm swing angle

trajectory to implement the agreement.

5   To be more specific, the gait goes through the

floating period of the first turning gait from the start

time Ts and reaches the second turning gait. The time at

which the floor reaction force vertical component has

increased to a predetermined magnitude is set as time Tm.

10   Further, in the latter half of a single stance period of

the second turning gait, the time at which the floor

reaction force vertical component has reduced to a certain

degree is set as time Ts2. Further, the gait goes through

the floating period of the second turning gait and reaches

15   the first turning gait. The time at which the floor

reaction force vertical component has increased to a

predetermined magnitude is set as time Tm2.

        Fig. 19 shows these times. The time Tm is preferably

set to be the moment substantially the entire surface of

20   the sole of the supporting leg foot 22 comes in contact

with the ground or immediately after that. The same

applies to time Tm2. Time Ts2 is preferably set to the

time of the moment at which the state wherein

substantially the entire surface of the sole of the

25   supporting leg foot 22 is in contact with the ground is

switched to tiptoe contact with the ground or at the time

immediately preceding it, as in the case of the start time

Ts.

A description will now be given of the relationship between the desired ZMP of Fig. 22 and these times Tm, Ts2 and Tm2 set in the afore-mentioned S110 of Fig. 15. In the second turning gait, the desired ZMP takes the heel of the supporting leg foot 22 as the beginning position and remains at this position until substantially the entire surface of the sole of the supporting leg foot 22 comes in contact with the ground, and then the desired ZMP begins to move to the center of the supporting leg foot 22. It is desired to set this moment the desired ZMP beings to move to the center of the supporting leg foot 22 as time Tm. Thereafter, the instant the movement of the desired ZMP to the tiptoe is completed by the time only the tiptoe of the supporting leg foot 22 comes in contact with the ground is preferably set as time Ts2. Furthermore, in the next first turning gait, the desired ZMP takes the heel of the supporting leg foot 22 as the beginning position and remains at this position until substantially the entire surface of the sole of the supporting leg foot 22 comes in contact with the ground, and then the desired ZMP begins to move to the center of the supporting leg foot 22. It is desired to set this moment the desired ZMP begins to move to the center of the supporting leg foot 22 as time Tm2.

The reason for setting as described above will be discussed hereinafter. The period for restoring

(adjusting) the body posture angle and the period for restoring (adjusting) the antiphase arm swing angle may be separately set.

After the processing from S010 to S022 shown in Fig. 13 is carried out, the processing proceeds to S024 and calculates an initial state of the normal gait. The initial state calculated here includes an initial horizontal body position/velocity (an initial body position and initial body velocity in the horizontal direction), an initial vertical body position/velocity (an initial body position and an initial body velocity in the vertical direction), an initial divergent component, an initial body posture angle and angular velocity, and an initial antiphase arm swing angle and angular velocity of the normal gait. The initial state is exploratorily calculated according to the flowchart of Fig. 23.

In the flowchart of Fig. 23, first, in S200, an initial state (a state at the start time Ts) of a desired foot position/posture, a desired arm posture, and a desired body posture angle (an inclination angle and a yaw angle) are determined on the basis of the gait parameters of the normal gait (the parameters set in S022 of Fig. 13 described above). The state here represents positions and posture angles and their changing rates (time differentiation).

In this case, the initial state of a desired foot position/posture of a supporting leg is determined by

generating, using a finite-duration setting filter, a foot
position/posture trajectory (a trajectory observed from a
next time's gait supporting leg coordinate system) from
the supporting leg foot position/posture at the start of
the first turning gait of the foot trajectory parameter
determined in S100 of Fig. 15 to the free leg foot
position/posture at the end of the second turning gait
until time Ts is reached. The initial state of a desired
foot position/posture of the free leg is determined by
generating, using a finite-duration setting filter, a foot
position/posture trajectory from the supporting leg foot
position/posture at the start of the current time gait
observed from a next time's gait supporting leg coordinate
system to the free leg foot position/posture at the end of
the first turning gait until time Ts is reached. The
initial state of a desired arm posture is determined to be
a reference arm posture at time Ts that is determined on
the basis of the reference arm posture trajectory
parameters determined in S104 of Fig. 15. To be more
specific, a total center-of-gravity position of both arms
5, 5 (a relative position with respect to the body 3) of a
desired arm posture, a lateral interval between right and
left hands (the distal ends of both arms 5, 5), and an
antiphase arm swing angle and an angular velocity are
determined. However, the antiphase arm swing angle and
the angular velocity are corrected so that they are
continuous in a boundary of gaits when a normal gait is

repeated, as it will be discussed hereinafter; therefore, they have been just temporarily determined.

For an initial state of a desired body posture angle, a reference body posture (an inclination angle and a yaw angle) and an angular velocity thereof at time Ts determined by the reference body posture trajectory parameter determined in S102 of Fig. 15 are determined as an initial state of the desired body posture angle. In the present embodiment, the reference body posture related to the inclination angle of the body 3 is a vertical posture, so that the initial state (the inclination angle and the angular velocity thereof) of the inclination angle in the desired body posture is zero.

Further, in the present embodiment, a desired foot position/posture trajectory, a floor reaction force vertical component trajectory, and a desired ZMP trajectory of a normal gait are determined independently from each other on the basis of a foot trajectory parameter, a floor reaction force vertical component trajectory parameter, and a ZMP trajectory parameter, respectively, which have been determined in the flowchart of Fig. 15. For example, a desired foot position/posture at each instant of a normal gait is determined on the basis of a foot trajectory parameter without depending on an instantaneous value of a floor reaction force vertical component.

Subsequently, in S202, (Xs, Vxs)(Xs: horizontal

position; Vxs: horizontal velocity), which is a candidate of an initial horizontal body position/velocity (that is, a candidate of the horizontal body position/velocity at the start time Ts), is provisionally determined. The

5   candidate (Xs, Vxs) to be provisionally determined may be arbitrary. For example, the horizontal body position/velocity in the initial state of the normal gait determined when the last time gait was generated may be used as a provisionally determined candidate (Xs, Vxs).

10   To simplify the explanation, a case where the initial state of a normal gait in the X-direction (longitudinal direction) on a sagittal plane is searched for will be taken as an example. However, for the initial state of a normal gait (the initial state that meets the aforesaid

15   boundary condition of a normal gait), it is actually required to search for the position and the velocity in the X direction (longitudinal direction) and the Y direction (lateral direction) separately or simultaneously.

Supplementally, there is no concept related to a yaw

20   rotation or a moment vertical component or the like about a vertical axis on the sagittal plane. For this reason, at least the yaw rotation and a moment vertical component are calculated in a three-dimensional space.

As an exploratory determining technique, a method in

25   which a pseudo-Jacobian (sensitivity matrix) is determined and then a next candidate is determined by the steepest descent method or the like, or the simplex method or the

like may be used. In the present embodiment, the steepest descent method will be used.

Next, the processing proceeds to S206 via S204 and determines the initial (time Ts) vertical body position/velocity (Zs, Vzs)(Zs: vertical position; Vzs: vertical velocity) so that the vertical body position/velocity is continuous and angles of joints, such as knees, will not be excessively large or small when the normal gait is repeated. More details regarding this have been described in, for example, PCT/JP02/13592 previously applied by the present applicant, and will be therefore omitted here.

After the processing of S206, the processing proceeds to S208 to provisionally generate a normal turning gait (the normal turning gait provisionally generated may be hereinafter referred to as the provisional gait). To be more specific, based on the gait parameters of the normal gait determined in S022 of Fig. 13 described above, a desired ZMP, a desired floor reaction force vertical component, a desired foot position/posture, a reference body posture, a desired arm posture, a floor reaction force horizontal component permissible range, and a floor reaction force moment vertical component permissible range at each instant from the start time Ts to the end time Te are sequentially determined. Then, gaits from time Ts to the end time Te are generated by sequentially determining the body position/posture, taking the horizontal body

position/velocity (Xs, Vxs) and the vertical body
position/velocity (Zs, Vzs) mentioned above as the initial
(time Ts) state of the body 3, and by using the aforesaid
dynamic model (the model in Fig. 12) so as to satisfy the
dynamic balance condition related to the determined
desired ZMP and the desired floor reaction force vertical
component and the condition of the floor reaction force
horizontal component permissible range. At this time, the
gaits are generated so that the body posture agrees with
the reference body posture as much as possible.

Moreover, an antiphase arm swing motion is determined
such that the condition related to the floor reaction
force moment vertical component, i.e., the floor reaction
force moment vertical component permissible range, is
satisfied.

Incidentally, the gait generation of the normal gait
is performed merely inside the gait generating device 100,
and the generated gaits are not output to a composite-
compliance operation determiner 104, which will be
discussed later, as desired values for driving the actual
robot 1.

The following will explain in detail the processing
for generating a normal gait by sequential calculation,
which is the processing in S208.

Fig. 24 is a subroutine flowchart illustrating the
processing.

The explanation will now be given. In S300, various

elements are initialized. Specifically, the start time Ts is substituted into time k for generating a provisional gait. Furthermore, a currently provisionally determined (Xs, Vxs) (determined in S202, or S216 or S218 of Fig. 23 to be discussed hereinafter) is substituted into the horizontal body position/velocity, and the latest (Zs, Vzs) determined in the aforesaid S206 is substituted into the vertical body position/velocity. In addition, an initial value of a reference body posture angle (angle at the start time Ts) is substituted into the body posture angle, and an initial value of a reference body posture angular velocity (an angular velocity at the start time Ts) is substituted into the body posture angular velocity.

A reference initial antiphase arm swing angle (angle at the start time Ts) is substituted into the antiphase arm swing angle, and a reference initial antiphase arm swing angular velocity (angular velocity at the start time Ts) is substituted into the antiphase arm swing angular velocity.

Subsequently, the processing proceeds to S304 via S302 and determines whether time k for generating a provisional gait is before gait end time (whether k ≤ Ts + Tcyc). If the determination result is YES, then the processing proceeds to a gait instantaneous value determining subroutine of S306 to determine a gait instantaneous value. Subsequently, the processing of the gait generating device 100 proceeds to S308 to increment

time k for generating a provisional gait by Δk, and then returns to S304.

Here, Δk is an interval of the generation of provisional gaits and normally set to agree with a control cycle Δt. If the dynamic accuracy of provisional gaits is not demanding, then Δk may be set to be longer than Δt in order to reduce the volume of calculation.

If the determination result of S304 is NO, then the processing proceeds to S310. The processing described above generates a normal gait (provisional gait) from its start to end before proceeding to S310.

A gait instantaneous value determining subroutine of S306 will now be explained in detail with reference to Fig. 25.

First, in S400 of Fig. 25, based on a normal gait parameter (the floor reaction force vertical component trajectory parameter), a value (current time value) of the desired floor reaction force vertical component shown in Fig. 19 at time k is determined. Further, in S402, a value (current time value) of the desired ZMP trajectory shown in Fig. 22 at time k is determined on the basis of a normal gait parameter (the ZMP trajectory parameter).

Then, the processing proceeds to S404 and determines the values (current time values) of desired positions/postures of both feet (desired foot positions/postures of both supporting leg and free leg), the reference body posture, and the reference arm posture

at time k on the basis of the normal gait parameters (the foot trajectory parameter, the reference body posture trajectory parameter, and the arm posture trajectory parameter). To be more specific about the reference arm

5   posture, the values (current time values) of the total center-of-gravity position of both arms 5, 5 (the relative position with respect to the body 3), the lateral interval between right and left hands (the distal ends of both arms 5, 5), and the antiphase arm swing angle are determined.

10   The current time value (the value at time k) of the desired foot position/posture is determined in the same manner as in the case where the foot position/posture at the start time Ts was determined in S200 of Fig. 23.

Then, the processing proceeds to S406 and calculates

15   a value (current time value) of the total center-of-gravity vertical position/velocity at time k that satisfies the desired floor reaction force vertical component (balances the sum of the inertial force in the vertical direction and gravity of the robot 1 with the

20   desired floor reaction force vertical component). To be more specific, the total center-of-gravity vertical position/velocity is calculated on the basis of, for example, the above Equation 01 and Equation 04 related to the dynamic model shown in Fig. 12. In other words,

25   Equation 01 and Equation 04 provide a relational expression (a dynamic equation related to the vertical direction of the total center of gravity of the robot 1)

indicating that the result obtained by multiplying the sum
of the total center-of-gravity vertical acceleration and
the gravity acceleration by a motion of the robot 1 by the
total mass of the robot 1 is equal to a floor reaction

5   force vertical component. Thus, the total center-of-
gravity vertical acceleration is determined from the
relational expression and the desired floor reaction force
vertical component.

The relational expression itself generally holds

10   without depending on a model of the robot 1. The total
center-of-gravity vertical velocity is calculated by
integrating the determined total center-of-gravity
vertical acceleration, and further, the total center-of-
gravity vertical velocity is integrated to calculate the

15   total center-of-gravity vertical position. More generally,
these calculations are carried out using the dynamic
relational expressions represented by the following
Equation 15 and Equation 16 (discretized equations of
Newton's dynamic equations).

20

Total center-of-gravity vertical velocity at time k
= Total center-of-gravity vertical velocity at time (k-Δk)
+ ((Floor reaction force vertical component/Total mass of
the robot) + acceleration of gravity) * Δk

25   (where the acceleration of gravity takes a negative value)

... Equation 15

Total center-of-gravity vertical position at time k

= Total center-of-gravity vertical position at time (k-Δk)

+ Total center-of-gravity vertical velocity at time k * Δk

... Equation 16

Subsequently, the processing proceeds to S408 and calculates the vertical body position that satisfies the total center-of-gravity vertical position. To be more specific, the vertical body position is calculated using, for example, Equation 04 related to the model in Fig. 12. Specifically, the vertical positions of the supporting leg mass point 2m and the free leg mass point 2m of the model in Fig. 12 are determined from the current time values of the desired foot positions/postures of the supporting leg and the free leg. Then, these determined vertical positions of the supporting leg mass point 2m and the free leg mass point 2m and the current time value of the total center-of-gravity vertical position determined in S407 are applied to Equation 04 so as to determine the vertical position of the body mass point 3m. Furthermore, the vertical body position is determined from the determined vertical position of the body mass point 3m and the current value of the desired body posture angle (the reference body posture angle set in S404 or the last time (time k-Δk) desired body posture angle determined in S414 to be discussed hereinafter).

The sequence then proceeds to S410 wherein the values

(current time values), at time k, of the floor reaction force horizontal component permissible range [Fxmin, Fxmax] shown in Fig. 20 are determined on the basis of the gait parameter (the parameter defining the floor reaction force horizontal component permissible range) determined in S108 of Fig. 15 described above.

Subsequently, the processing proceeds to S411 wherein the value (current time value), at time k, of the floor reaction force moment vertical component permissible range [Mzmin, Mzmax] shown in Fig. 21 is determined on the basis of the gait parameter (the parameter defining the floor reaction force moment vertical component permissible range) determined in S109 of Fig. 15 described above.

Then, the processing proceeds to S412 wherein the current time values of the desired horizontal body acceleration and the desired body posture acceleration are determined such that the dynamic balance condition related to the desired ZMP (the condition in that the horizontal component of a moment generated about the desired ZMP by a resultant force of an inertial force and the gravity of the robot 1 is zero) is satisfied. The horizontal body acceleration and the body posture angular acceleration (more specifically, the body inclination angular acceleration) are determined such that the floor reaction force horizontal component Fx does not exceed [Fxmin, Fxmax]. Further, the current time value of the desired antiphase arm swing angular acceleration is determined

such that the floor reaction force moment vertical component Mz does not exceed [Mzmin, Mzmax].

In the body posture angle, the yaw angle is determined so as to agree with the yaw angle of the reference body posture angle. Regarding the desired arm posture, components other than the antiphase arm swing angle are determined to agree with the reference arm posture. At this time, the desired body inclination angle and the desired antiphase arm swing angle are determined to follow the reference body inclination angle and the reference antiphase arm swing angle, respectively, as much as possible, while satisfying the aforesaid condition. This will be explained in detail below.

At this point, the instantaneous values (current time values) of the foot position/posture and the vertical body position have been determined as described above. Regarding the arm posture, the components other than the antiphase arm swing angle have been determined to agree with those of the reference arm posture. Therefore, once the remaining horizontal body position, body posture angle and antiphase arm swing angle are determined, the desired motion of the robot 1 will be uniquely determined. Hence, all floor reaction forces will be also uniquely determined. In the present embodiment, the desired floor reaction force vertical component and the desired ZMP of a normal gait are defined by the floor reaction force vertical component trajectory parameters and the desired ZMP

trajectory parameters, respectively, determined in S022 of Fig. 13 described above.

When generating a gait, if the body inclination mode is primarily used to satisfy a desired ZMP (to set the horizontal component of a floor reaction force moment about a desired ZMP to zero) without using the aforesaid body translational mode much, then the body posture angle may become excessively large. To prevent this, therefore, the body translational mode should be used as much as possible. However, the body translational mode involves floor reaction force horizontal component changes, so that slippage may occur if the body translational mode is intensely effected when the floor reaction force horizontal component permissible range is narrow. In this case, depending upon the body inclination mode is an inevitable choice. Especially during a period in which the floor reaction force horizontal component permissible range is zero, as in the aforesaid running gait, it is impossible to generate a gait that produces a floor reaction force horizontal component. Hence, depending upon the body inclination mode is an inevitable choice.

Meanwhile, an antiphase arm swing motion allows only the floor reaction force moment vertical component to be changed without changing any of the horizontal component of a floor reaction force moment about a desired ZMP and the floor reaction force horizontal component, so that it can be used to prevent the floor reaction force moment

vertical component from exceeding the aforesaid floor reaction force moment vertical component permissible range. Considering the above, in the present embodiment, the horizontal body acceleration, the body posture angular

5   acceleration, and the antiphase arm swing acceleration are determined according to the flowchart shown in Fig. 26. For the convenience of understanding, regarding the determination of the horizontal body acceleration and the body posture angular acceleration (the angular

10 acceleration of an inclination angle of the body 3), a case where the horizontal body acceleration and the body posture angular acceleration in the X direction (longitudinal direction) are determined on a sagittal plane will be taken as an example. Actually, however, the

15 horizontal body acceleration and the body posture angular acceleration in the Y direction (lateral direction) are also determined in the same manner as that for the X direction.

First, in S500, the value of the reference body yaw

20 angle at time k is substituted into the desired body yaw angle. Further, the value of a reference arm posture at time k is substituted into the desired arm posture, excluding the antiphase arm swing angle and the angular velocity component of an arm posture.

25 Then, in S502, it is determined whether the current time (the value of a timer for generating a normal gait) k is in the period of restoring a body posture angle and an

antiphase arm swing angle (the period of restoring a body posture angle and an antiphase arm swing angle being the period from time Tm to time Ts2 and the period from time Tm2 to Te in the case of a normal gait). The processing proceeds to S504 if the determination result of S502 is NO, or to S530 if the determination result is YES.

In S504, a horizontal body acceleration αtmp is determined, which is required to satisfy the current (time k) desired ZMP if the robot 1 is made to perform a motion of the body translational mode from a last time instantaneous gait state (the gait state at time k-1) of the robot 1, with the angular acceleration of the body inclination mode being set to zero. The αtmp is determined using, for example, the above Equation 03y related to the dynamic model of Fig. 12 described above. To be more specific, for example, time series values of desired foot positions/postures determined up to the current time k are used to determine the vertical accelerations of the supporting leg mass point 2m and the free leg mass point 2m at the current time k, and a desired foot position/posture at the current time k (current time) is used to determine the vertical positions of the supporting leg mass point 2m and the free leg mass point 2m. Furthermore, the floor reaction force vertical position at the current time k (current time) is used to determine the vertical position of the body mass point 3m, and the vertical acceleration of the body mass point 3m at

the current time k is determined by using time series
values of the desired vertical body positions determined
up to the current time k. Then, these determined values
are substituted into the above Equation 03y, and an
equation obtained by setting My and d2θby/dt2 of the
Equation 03y to zero is solved on d2Xb/dt2 so as to
determine the body mass point horizontal acceleration as
the horizontal body acceleration αtmp. A more precise
dynamic model may be used to exploratorily determine the
horizontal body acceleration αtmp that sets the horizontal
component of the floor reaction force moment about the
desired ZMP to zero. Further, in the present embodiment,
the reference body posture related to the inclination
angle of the body 3 is the vertical posture and the body
posture angular acceleration (the angular acceleration of
the inclination angle of the body 3) in the reference body
posture is zero, so that the angular acceleration in the
body inclination mode was set to zero to determine the
horizontal body acceleration αtmp. If, however, the
reference body posture trajectory parameters are set so
that the inclination angle of the reference body posture
changes and if the reference body posture angular
acceleration (the reference angular acceleration of the
inclination angle of the body 3) at the current time k
determined thereby is not zero, then the angular
acceleration in the body inclination mode may be set to
the value of the reference body posture angular

acceleration, which is not zero, to determine the horizontal body acceleration αtmp by using a dynamic model (for example, d2θby/dt2 of Equation 03y may be set to a reference body posture angular acceleration that is not zero to determine the horizontal body acceleration αtmp in the same manner as described above).

Next, the processing proceeds to S506 wherein a floor reaction force horizontal component Fxtmp at time k when the horizontal body acceleration is αtmp is determined using a dynamic model. In the present embodiment, Fxtmp is determined using Equation 02x of the dynamic model. In other words, Fxtmp is determined according to the following Equation 17, where d2Xsup/dt2 and d2Xswg/dt2 denote the supporting leg foot mass point horizontal acceleration and the free leg foot mass point horizontal acceleration at time k.

Fxtmp = mb * αtmp + msup * d2Xsup/dt2

                        + mswg * d2Xswg/dt2   ... Equation 17

An example of Fxtmp determined as described above is shown in Fig. 27. In Fig. 27, a portion wherein Fxtmp exceeds the floor reaction force horizontal component permissible range [Fxmin, Fxmax] is hatched.

Subsequently, the processing proceeds to S508 wherein a horizontal body acceleration α in the body translational mode and a floor reaction force horizontal component Fx

generated thereby, and a body angular acceleration β in the body inclination mode are determined as shown below (S508 to S516).

Specifically,

If Fxtmp > Fxmax, then the processing proceeds to S510 wherein Fx is determined according to the following equation.

Fx = Fxmax   ... Equation 18

If Fxtmp < Fxmin, then the processing proceeds to S512 wherein Fx is determined according to the following equation.

Fx = Fxmin   ... Equation 19

In other cases, that is, if Fxtmp lies within the floor reaction force horizontal component permissible range [Fxmin, Fxmax], then the processing proceeds to S514 wherein Fx is determined according to the following equation.

Fx = Fxtmp   ... Equation 20

In any case, the processing proceeds to S516 wherein the horizontal body acceleration α and the body posture angular acceleration (body inclination angular

acceleration) β are determined according to the following equations.

$$\alpha = \alpha tmp + (Fx - Fxtmp)/\Delta Fp \qquad \ldots \text{ Equation 21}$$

5

$$\beta = (\alpha tmp - \alpha) * \Delta Mp/\Delta Mr \qquad \ldots \text{ Equation 22}$$

where ΔFp, ΔMp, and ΔMr are determined according to the above Equations 06, 07, and Equation 09, respectively.

Supplementally, if higher accuracy of the dynamic

10 calculation is required, then, after determining the body angular acceleration β as described above, the horizontal body acceleration α in the body translational mode should be analytically or exploratorily determined by using a more precise dynamic model so that a motion obtained by

15 combining the body translational mode and the body inclination mode of the above determined body angular acceleration β satisfies the desired ZMP. As an exploratory determining method, a method in which a pseudo-Jacobian (sensitivity matrix) is determined and

20 then a next candidate is determined by the pseudo-Newton method or the like, or the simplex method or the like may be used.

Further, in order to strictly prevent the floor reaction force horizontal component Fx from exceeding the

25 floor reaction force horizontal component permissible range [Fxmin, Fxmax], a set of the horizontal body acceleration α and the body angular acceleration β may be

exploratorily searched for such that Fx=Fxmax and the horizontal component of the floor reaction force moment about the desired ZMP is zero in S510 and also Fx=Fxmin and the horizontal component of the floor reaction force moment about the desired ZMP is zero in S512.

Fig. 28 shows Fx determined as described above. Fx has been limited (saturated) so that a value of Fxtmp does not exceed the floor reaction force horizontal component permissible range [Fxmin, Fxmax]. More specifically, Fxtmp is directly used as Fx if Fxtmp based on the horizontal body acceleration αtmp by the body translational mode alone lies within the permissible range [Fxmin, Fxmax]. If Fxtmp based on the horizontal body acceleration αtmp by the body translational mode alone exceeds an upper limit of the permissible range [Fxmin, Fxmax] or reduces below a lower limit thereof, then Fx is forcibly limited to Fxmax and Fxmin, respectively. Especially in a floating period of a running gait, Fxmax=Fxmin=0 applies all the times, so that Fx=0.

Fig. 29 shows the body posture angular acceleration β determined as described above. Thus, an insufficient portion of the floor reaction force moment caused by limiting the acceleration in the body translational mode so as to prevent Fx generated by the body translational mode from exceeding the permissible range [Fxmin, Fxmax] (more specifically, the moment obtained by subtracting a moment component produced by a limited body horizontal

motion and the motions of both legs 2, 2 from an inertial force moment required for reducing the horizontal component of a floor reaction force moment about the desired ZMP to zero) has been compensated for by the body

5 inclination mode. During a floating period of a running gait, the horizontal body acceleration α by the body translational mode is always limited to zero, so that the insufficient portion of the floor reaction force moment is compensated for only by the body posture angular

10 acceleration β by the body inclination mode.

Subsequently, the processing proceeds to S518 to determine a floor reaction force moment vertical component Mztmp when a motion in which, for example, a horizontal body acceleration in the body translational mode is α, a

15 body angular acceleration (body inclination angular acceleration) in the body inclination mode is β, a body acceleration in the body yaw rotation mode (body yaw angular acceleration) is a reference yaw angular acceleration d2θbzref/dt2, and an antiphase arm swing

20 angular acceleration βa is a reference antiphase arm swing angular acceleration d2θazref/dt2, is performed. Hereinafter, d2θbzref/dt2 will be βbref, and d2θazref/dt2 will be βaref.

To be more specific, Mz obtained by substituting

25 Equation 1001 through Equation 1004 into Equation 03z is Mztmp.

$$d2Xb/dt2 = \alpha x \qquad \text{... Equation 1001}$$

$$d2Yb/dt2 = \alpha y \qquad \text{... Equation 1002}$$

$$d2\theta bz/dt2 = \beta bref \qquad \text{... Equation 1003}$$

$$d2\theta az/dt2 = \beta aref \qquad \text{... Equation 1004}$$

5

where αx denotes an X component of the horizontal body acceleration α, and αy denotes a Y component of the horizontal body acceleration α. Furthermore, a horizontal body position at time k-1 is substituted into Xb and Yb,

10 and a value of time k is substituted into Xzmp, Yzmp, Xsup, d2Ysup/dt2, Xswg, and d2Yswg/dt2.

Fig. 32 shows an example Mztmp determined as described above. In Fig. 32, the portion of Mztmp that exceeds the floor reaction force moment vertical component

15 permissible range [Mzmin, Mzmax] is shown by hatching.

Next, the processing proceeds to S520 wherein an antiphase arm swing angular acceleration βa is determined as shown below (S520 ~ S528).

Specifically,

20 If Mztmp > Mzmax, then the processing proceeds to S522 wherein Mz is determined according to the following equation.

$$Mz = Mzmax \qquad \text{... Equation 1018}$$

25

If Mztmp < Mzmin, then the processing proceeds to S524 wherein Mz is determined according to the following

equation.

$$Mz = Mzmin \quad \text{... Equation 1019}$$

5   In other cases, that is, if Mztmp lies within the floor reaction force horizontal component permissible range [Mzmin, Mzmax], then the processing proceeds to S526 wherein Mz is determined according to the following equation.

10

$$Mz = Mztmp \quad \text{... Equation 1020}$$

In any case, the processing proceeds to S528 wherein the antiphase arm swing angular acceleration βa is

15   determined according to the following equation.

$$\beta a = \beta aref + (Mztmp-Mz)/\Delta Maz \quad \text{... Equation 1021}$$

where ΔMaz is determined according to Equation 09a.

20   The following will explain the processing from S518 to S528.

Mz determined as described above denotes a floor reaction force moment vertical component from a motion of the entire robot, including an antiphase arm swing.

25   In the above processing, the antiphase arm swing angular acceleration βa has been determined such that the Mz does not exceed the floor reaction force moment

vertical component permissible range [Mzmin, Mzmax]. To be more specific, Mz has been determined to be limited (saturated) so that a value of Mztmp does not exceed the floor reaction force horizontal component permissible range [Mzmin, Mzmax], as shown in Fig. 33. More detailedly, Mztmp is directly used as Mz if Mztmp lies within the permissible range [Mzmin, Mzmax]. If Mztmp exceeds an upper limit of the permissible range [Mzmin, Mzmax] or reduces below a lower limit thereof, then Mz is forcibly limited to Mzmax and Mzmin, respectively. Especially in a floating period of a running gait, Mzmax=Mzmin=0 applies all the times, so that Mz=0.

A moment vertical component Maz to be generated by an antiphase arm swing in order to prevent Mz from exceeding the floor reaction force moment vertical component permissible range [Mzmin, Mzmax] is obtained by (Mz-Mztmp). Maz(= Mz-Mztmp) is shown in Fig. 34.

The antiphase arm swing angular acceleration βa can be obtained by adding the result obtained by dividing Maz by an equivalent inertial moment ΔMaz of an antiphase arm swing to a reference antiphase arm swing angular acceleration βaref (a value obtained by subjecting a reference antiphase arm swing angle to second order differentiation). Specifically, βa is determined according to the above Equation 1021. The antiphase arm swing angular acceleration βa is shown in Fig. 35.

As described above, in the processing from S504 to

S528, the antiphase arm swing angular acceleration βa is determined such that the floor reaction force moment vertical component Mz generated by a motion of the entire robot, including an antiphase arm swing, does not exceed the permissible range [Mzmin, Mzmax] (such that the floor reaction force moment vertical component Mztmp offsets (cancels) the portion of the floor reaction force moment vertical component Mztmp that exceeds the permissible range, the floor reaction force moment vertical component Mztmp being generated when an antiphase arm swing angular acceleration is set to agree with the reference antiphase arm swing angular acceleration βaref).

Supplementally, to strictly prevent the floor reaction force moment vertical component Mz from exceeding the floor reaction force moment vertical component permissible range [Mzmin, Mzmax], the antiphase arm swing angular acceleration βa should be analytically or exploratorily determined by using a more precise dynamic model in place of the processing from S504 to S528. As an exploratory determining method, a method in which a pseudo-Jacobian (sensitivity matrix) is determined and then a next candidate is determined by the pseudo-Newton method or the like, or the simplex method or the like may be used.

The above processing is performed if time k is not found during the period of restoring a body posture angle and an antiphase arm swing angle.

If a determination result of S502 is YES, then the following processing will be carried out. First, the processing proceeds to S530 to determine the horizontal body acceleration α required to satisfy the desired ZMP of current time (time k) when the robot 1 is made to perform a motion of the body translational mode, with the angular acceleration in the body inclination mode being set to zero, from the last time instantaneous gait state (the gait state at time k-1) of the robot 1, and this is determined as a final horizontal body acceleration.

Next, the processing proceeds to S532 wherein the floor reaction force horizontal component Fx in the aforesaid case is determined.

Next, the processing proceeds to S534 wherein the body posture angular acceleration (the body inclination angular acceleration) β is determined to be zero. The body yaw angular acceleration is determined to be the reference body yaw angular acceleration βbref (the value obtained by subjecting the reference body yaw angle to second order differentiation).

Lastly, the processing proceeds to S536 wherein the reference antiphase arm swing angular acceleration βaref (the value obtained by subjecting the reference antiphase arm swing angle to second-order differentiation) is substituted into the antiphase arm swing angular acceleration βa.

The above is the processing carried out if the

determination result of S502 is YES. More specifically,
in this case, the body posture angular acceleration (the
body inclination angular acceleration and the body yaw
angular acceleration) is set to agree with the reference

5   body posture angular acceleration, and the antiphase arm
swing angular acceleration is set to agree with a
reference antiphase arm swing angular acceleration. It is
expected that this setting will not cause a floor reaction
force generated by a motion to exceed the floor reaction

10   force horizontal component permissible range and the floor
reaction force moment vertical component permissible
range; therefore, determining as described above will
present no problem.

After the processing of S528 or S536, the processing

15   proceeds to S414 of Fig. 25 wherein the horizontal body
acceleration determined in S412 is sequentially integrated
(cumulative addition from time Ts to current time k) so as
to determine a horizontal body velocity, and further, the
horizontal body velocity is sequentially integrated

20   (cumulative addition from time Ts to current time k) so as
to determine a horizontal body position (current time
value). Further, the body posture angular acceleration
determined in S412 is sequentially integrated (cumulative
addition from time Ts to the current time k) so as to

25   determine a body posture angular velocity, and further,
the body posture angular velocity is sequentially
integrated (cumulative addition from time Ts to the

current time k) so as to determine a body posture angle (current time value).

The processing then proceeds to S416 wherein the antiphase arm swing acceleration βa determined in S412 is sequentially integrated (cumulative addition from time Ts to the current time k) so as to determine an antiphase arm swing velocity, and further, the determined antiphase arm swing velocity is sequentially integrated (cumulative addition from time Ts to the current time k) so as to determine an antiphase arm swing angle θaz (current time value).

After the normal gait instantaneous value determining subroutine of S306 in Fig. 24 is carried out, the processing proceeds to S308 wherein the value of time k for generating a gait is incremented by a gait generation interval Δk. Then, the processing returns to S304 to repeat the processing of S306 and S308 as long as the condition shown in S304 is satisfied. When the condition shown in S304 is no longer satisfied, that is, when the generation of provisional gaits up to the end (time Te = Ts+Tcyc) is completed, the processing proceeds to S310.

For a normal gait, an initial body posture angle and its angular velocity must be determined such that motional states of the robot 1 are not discontinuous at boundaries when the normal gait is repeated.

Hence, in S310, a pattern of a ZMP-converted value (hereinafter referred to as the body posture restoring

moment ZMP-converted value and abbreviated to ZMPrec) of a floor reaction force moment for generating a body posture angular acceleration for setting a body posture angular velocity back to an initial value (the value at time Ts)

5   by time Te is set.

This will be explained in detail below.

The following will discuss the procedure for setting a body posture angular velocity back to an initial value (the value at time Ts) by generating a body posture

10   angular acceleration by using the body inclination mode during the body posture angle and antiphase arm swing angle restoring period (the period from time Tm to time Ts2 and from time Tm2 to Te). A body posture angular acceleration pattern for this purpose is denoted by $\beta(k)$.

15   In periods other than the above-mentioned period, $\beta(k)=0$ will apply.

In the body inclination mode, generating the body posture angular acceleration $\beta(k)$ will generate a floor reaction force moment $\beta(k)*\Delta Mr$. As a result, if the floor

20   reaction force vertical component at that instant is denoted by $Fz(k)$, then $ZMP(k)$ calculated from a motion (rather than a desired ZMP) will be shifted by ΔZMP determined according to the following equation.

25   $$\Delta ZMP(k) = -\beta(k)*\Delta Mr/Fz(k) \quad \text{... Equation 23}$$

Therefore, if the pattern of ΔMr and the pattern of

Fz(k) have been determined (known), then the body posture angular velocity can be set back to the initial value (the value at time Ts), that is, the body posture angular velocity in an initial (time Ts) state of the reference body posture trajectory by appropriately setting a pattern of ΔZMP(k) to generate a body posture angular acceleration pattern that satisfies Equation 23.

The aforesaid body posture restoring moment ZMP-converted value (ZMPrec) means ΔZMP(k) that has been appropriately set as described above. Strictly speaking, ΔMr varies when setting the body posture restoring moment ZMP-converted value by using the above Equation 23, but it may be approximately set at a constant value. This is because the normal gait is merely generated for temporary use and not used to make an actual robot follow the gait, so that the dynamic accuracy of a normal gait does not have to be very high.

Fig. 30 illustrates an example of ZMPrec. In Fig. 30, as a pattern of ZMPrec, trapezoidal patterns are formed for the period from time Tm to time Ts2 and for the period from time Tm2 to time Te. The times of break points of the trapezoidal portions are set to agree with the times of break points of a desired ZMP pattern in the period between time Tm and time Ts2 and the period from Tm2 to Te (refer to Fig. 22). This is because correction of the desired ZMP pattern of a current time gait will be easier, as it will be discussed hereinafter.

Substituting ZMPrec(k) into ΔZMP(k) of Equation 23 provides the following equation.

$$\beta(k) = -ZMPrec(k)*Fz(k)/\Delta Mr \qquad \text{... Equation 24}$$

5

Therefore, β(k) determined in this Equation 24 will be as indicated by the solid lines in Fig. 31. The dashed lines in Fig. 31 indicate the body posture angular acceleration during the period from time Ts to time Tm and

10   the period from time Tm2 to Te (indicated by the solid lines in Fig. 29). (Hereinafter, (k) may be omitted if a value is obviously the value at time k.)

The initial (time Ts) body posture angle is set to agree with the initial (time Ts) reference body posture

15   angle.

Further, the initial body posture angular velocity is determined to satisfy Equations 37a and 37b.

Terminal body posture angle - Initial body posture angle

20   = Second-order integration of a body posture angular acceleration that has been determined to satisfy a floor reaction force horizontal component permissible range

+ Second-order integration of a body posture angular acceleration generated by ZMPrec

25   + Initial body posture angular velocity * Cycle of normal gait

...... Equation 37a

Terminal body posture angular velocity - Initial body posture angular velocity

= First-order integration of a body posture angular acceleration that has been determined to satisfy a floor reaction force horizontal component permissible range

+ First-order integration of a body posture angular acceleration generated by ZMPrec

...... Equation 37b

The integration period of the first term of the right side of each of Equations 37a and 37b is the period combining the period from time Ts to Tm and the period from Ts2 to Tm2, while the integration period of the second term of the right side is the period combining the period from time Tm to Ts2 and the period from Tm2 to Te.

To explain more specifically, in a normal gait, an initial state posture angle and an angular velocity observed from a supporting leg coordinate system of a first turning gait (a next time's gait supporting leg coordinate system) must agree with a terminal body posture angle and angular velocity, respectively, observed from a supporting leg coordinate system of the next first turning gait (the next but two time gait supporting leg coordinate system). Therefore, in the present embodiment, the initial (time Ts) body posture angle is determined to be the value of the initial (time Ts) reference body posture

angle, and this value and the value obtained by subjecting this value to coordinate conversion into a value observed from the next time's gait supporting leg coordinate system by a matrix (matrix of rotational coordinate conversion) based on a total turning angle (turning angle about a vertical axis) of the robot 1 in a normal gait are substituted into the initial body posture angle and the terminal body posture angle, respectively, in the left side of Equation 37a.   The body posture angular acceleration determined in S518 of Fig. 26 described above is used as the body posture angular acceleration related to the integration of the first term of the right side of Equations 37a and 37b.

Then, the initial body posture angular velocities of Equations 37a and 37b and the heights of the trapezoids of ZMPrec (the trapezoidal patterns shown in Fig. 30) related to the integration of the second terms of the right sides of Equations 37a and 37b are taken as unknown numbers (However, the times of the break points of the trapezoidal patterns of ZMPrec are determined beforehand.   Further, a trapezoidal height acyc1 of ZMPrec of a first turning gait and a trapezoidal height acyc2 of ZMPrec of a second turning gait are set to have the same value.)   An initial body posture angular velocity determined by solving the simultaneous equation of Equations 37a and 37b including the unknown numbers is decided as a new initial body posture angular velocity.   In this case, the terminal body

posture angular velocity in Equation 37b is obtained by coordinate-converting the initial body posture angular velocity, which is an unknown number, into a value observed from a next time's supporting leg coordinate

5   system by a matrix based on the above total turning angle of a normal gait.

Subsequently, the processing proceeds to S312 wherein an amount of influence exerted by a body inclination restoring moment ZMP-converted value (ZMPrec) pattern on a

10   horizontal body position and velocity is determined on the basis thereof, and the determined amount is added to the terminal horizontal body position and velocity.

This processing will be explained. The details thereof have been explained in PCT/JP02/13592 by the

15   present applicant, so that only a brief explanation will be given here.

During the period from time Ts to Tm and the period from time Ts2 to Te, if the body posture angular acceleration β is changed to generate the body inclination

20   restoring moment ZMP-converted value (ZMPrec) pattern, as described above, then the body posture angular acceleration β is determined according to the following equation.

25   $$\beta = -ZMPrec*Fz/\Delta Mr \qquad \text{... Equation 1025}$$

The horizontal body acceleration that satisfies the

desired ZMP when no body inclination restoring moment is generated is αtmp as determined in S532. When the body posture angular acceleration β is changed as described above, the horizontal body acceleration α required to satisfy the desired ZMP is determined according to the following equation.

$$\alpha = \alpha tmp - (\Delta Mr/\Delta Mp) * \beta \quad \text{... Equation 1026}$$

From Equations 1025 and 1026,

$$\alpha = \alpha tmp + ZMPrec * Fz/\Delta Mp \quad \text{... Equation 1027}$$

In other words, the acceleration is increased by an equivalent to the second term of the right side of Equation 1027 by the body inclination restoring moment ZMP-converted value (ZMPrec).

Using the linearity of the equations, the terminal horizontal body velocity obtained when the body posture angular acceleration β is changed to generate the body inclination restoring moment ZMP-converted value (ZMPrec) pattern as described above will be determined by adding the first-order integration of (ZMPrec*Fz/ΔMp) from time Ts to Te to the terminal horizontal body velocity obtained when the body inclination restoring moment ZMP-converted value (ZMPrec) pattern is not generated, i.e., the terminal value of the horizontal body velocity determined

in S414. Further, the terminal horizontal body position obtained when the body posture angular acceleration β is changed to generate the body inclination restoring moment ZMP-converted value (ZMPrec) pattern as described above will be determined by adding the second-order integration of (ZMPrec*Fz/ΔMp) from time Ts to Te to the terminal horizontal body position obtained when the body inclination restoring moment ZMP-converted value (ZMPrec) pattern is not generated, i.e., the terminal value of the horizontal body position determined in S414.

After completing the processing of S312, the processing proceeds to S314 wherein an antiphase arm swing restoring angular acceleration (βarec) pattern is determined such that the antiphase arm swing angular velocities at a start and an end agree.

To be more specific, the antiphase arm swing restoring angular acceleration patterns are set to be trapezoidal, as shown in Fig. 36, and a trapezoidal height azcyc2 in the period from time Tm to Ts2 and a trapezoidal height azcyc1 in the period from time Tm2 to Te are set to be the same. The trapezoidal heights azcyc1 and azcyc2 are determined such that the sum of the integrated value of βarec from time Ts to Te and the integrated value of the above determined antiphase arm swing acceleration βa for preventing the floor reaction force moment vertical component Mz from exceeding a permissible range becomes zero. The trapezoidal heights in the two periods do not

have to be the same.

Supplementally, a floor reaction force moment
vertical component (Mazrec) generated by the antiphase arm
swing restoring angular acceleration pattern determined as
described above is as shown in Fig. 37. Accordingly, as
shown in Fig. 38, the floor reaction force moment vertical
component Mz generated by a motion of the robot, including
an antiphase arm swing, will be eventually the sum of
Mztmp of Fig. 32, Maz of Fig. 34, and Mazrec of Fig. 37,
i.e., the sum of Mz of Fig. 33 and Mazrec of Fig. 37. In
the period from time Tm to Ts2 and the period from time
Tm2 to Te, trapezoidal restoring moments are added. These
periods are set so as to provide a sufficiently wide
permissible range; therefore, the floor reaction force
moment vertical components generated by motions of the
robot, including antiphase arm swings, will not exceed the
permissible range.

The processing then proceeds to S316 wherein an
initial (time Ts) antiphase arm swing angle and angular
velocity of a normal gait are determined.

To be more specific, the initial antiphase arm swing
angular velocity is determined according to the following
equation.

Initial antiphase arm swing angular velocity

= Reference initial antiphase arm swing angular velocity

- (Antiphase arm swing angle when βarec is 0

+ Second order integration of βarec pattern) /Tcyc

... Equation 1030

where in the above equation, the antiphase arm swing

angle when βarec is zero is the antiphase arm swing angle

5   (the antiphase arm swing angle at time Te) determined in

S416. The second order integration of βarec refers to a

second order integrated value of the antiphase arm swing

restoring angular acceleration from time Ts to Te set as

shown in Fig. 36. The reference initial antiphase arm

10   swing angular velocity refers to the value of the

aforesaid reference antiphase arm swing angular velocity

(the first order differential value of the reference

antiphase arm swing angle θaref) at time Ts.

The initial antiphase arm swing angle is set to agree

15   with the reference initial antiphase arm swing angle.

Alternatively, based on a finally determined antiphase arm

swing angular acceleration (that is, the above determined

sum of antiphase arm swing acceleration βa and the

restoring angular acceleration βarec for preventing the

20   floor reaction force moment vertical component Mz from

exceeding a permissible range) and the above determined

initial antiphase arm swing angular velocity, the average

value of the difference between an arm swing angle

calculated when an initial antiphase arm swing angle is

25   set to agree with a reference initial antiphase arm swing

angle and a reference antiphase arm swing angle, or an

average value of the maximum value and the minimum value

of the difference may be determined, and then the value
obtained by subtracting a half of the determined average
value from the reference initial antiphase arm swing angle
may be determined as the final initial antiphase arm swing

5   angle. This arrangement makes it possible to prevent the
absolute value of the difference between a calculated arm
swing angle and the reference antiphase arm swing angle
from becoming excessively large.

       One of the reasons that times Ts, Tm, Ts2, and Tm2

10   have been set as described above is to prevent the floor
reaction force horizontal component Fx from exceeding the
permissible range [Fxmin, Fxmax] even if the body posture
angular acceleration β is generated to set the body
posture angular velocity back to the initial angular

15   velocity of a reference body posture trajectory during the
period from time Tm to Ts2 and the period from time Tm2 to
Te. In other words, the floor reaction force horizontal
component permissible range is sufficiently wide in the
period from time Tm to Ts2 and the period from time Tm2 to

20   Te, so that the floor reaction force horizontal component
Fx does not exceed the permissible range even if the body
posture angular acceleration β is generated to restore the
body posture angular velocity, while satisfying the
desired ZMP.

25   Another reason that the times Ts, Tm, Ts2, and Tm2
have been set as described above is to prevent the floor
reaction force moment vertical component Mz from exceeding

the permissible range [Mzmin, Mzmax] even if the antiphase arm swing angular acceleration βa is generated to set the antiphase arm swing angular velocity back to the initial angular velocity of a reference antiphase arm swing angle

5   trajectory during the period from time Tm to Ts2 and the period from time Tm2 to Te. In other words, the floor reaction force moment vertical component permissible range is sufficiently wide in the period from time Tm to Ts2 and the period from time Tm2 to Te, so that the floor reaction

10   force moment vertical component Mz does not exceed the permissible range even if the antiphase arm swing angular acceleration βa is generated to restore the antiphase arm swing angular velocity.

After the processing of S316 of Fig. 24 is completed

15   as described above, the processing proceeds to S210 of Fig. 23 wherein the terminal horizontal body position and velocity of a generated gait (provisional normal gait) are converted into values observed from a supporting leg coordinate system (the coordinate system of X"', Y"', and

20   Z"' shown in Fig. 17) associated with the supporting leg of that particular instant, and the values are defined as (Xe, Vxe)(Xe: Terminal body horizontal position; and Vxe: Terminal horizontal body velocity).

Subsequently, the processing proceeds to S212 wherein

25   the difference between the initial horizontal body position/velocity (Xs, Vxs) and the terminal horizontal position/velocity (Xe, Vxe) is calculated, as illustrated.

This difference (Xs-Xe, Vxs-Vxe) is referred to as a horizontal body position/velocity boundary condition error (errx, errvx). In a normal gait, the boundary condition must be satisfied, so that (Xs, Vxs) and (Xe, Vxe) must agree. Hence, the horizontal body position/velocity boundary condition error (errx, errvx) must be zero or substantially zero. In the present embodiment, (Xs, Vxs) that sets the horizontal body position/velocity boundary condition error (errx, errvx) to substantially zero is exploratorily determined.

Subsequently, the processing proceeds to S214 wherein it is determined whether the calculated horizontal body position/velocity boundary condition error (errx, errvx) falls within the permissible range appropriately set beforehand. Instead of setting the permissible range of a horizontal body position/velocity boundary condition error as described above, it may be determined whether the difference between an initial divergent component $(Xs+Vxs/\omega 0)$ and a terminal divergent component $(Xe+Vxe/\omega 0)$ and the difference between an initial convergent component $(Xs-Vxs/\omega 0')$ and a terminal convergent component $(Xe-Vxe/\omega 0')$ respectively fall within certain permissible ranges. As previously mentioned, $\omega 0$ and $\omega 0'$ denote certain predetermined values.

If the determination result of S214 is NO, then the processing proceeds to S216. In this S216, a plurality of (two in the present embodiment) initial value candidates

(Xs + ΔXs, Vxs) and (Xs, Vxs + ΔVxs) is determined in the vicinity of (Xs, Vxs). Here, ΔXs and ΔVxs mean predetermined minute variation amounts associated with Xs and Vxs, respectively. Then, taking each of these initial value candidates as an initial state of the horizontal body position/velocity, a normal gait is generated using gait parameters by the same processing as that of the above S208. Further, the terminal body position/velocity of the generated normal gait are converted to obtain values (Xe+ΔXe1, Vxe+ΔVxe1) and (Xe+ΔXe2, Vxe+ΔVxe2) observed from a supporting leg coordinate system (the coordinate system of X"', Y"', and Z"' shown in Fig. 17) associated with the supporting leg at that particular instant. Here, (Xe+ΔXe1, Vxe+ΔVxe1) means the terminal body position/velocity that corresponds to (Xs+ΔXs, Vxs), and (Xe+ΔXe2, Vxe+ΔVxe2) corresponds to the terminal body position/velocity that corresponds to (Xs, Vxs+ΔVxs). In the processing for generating a normal gait (provisional gait) in this case, the initial state (the state at time Ts) of a variable other than the horizontal body position/velocity may be set to the same value as that in a case where, for example, the initial value candidate of the horizontal body position/velocity is set to (Xs, Vxs). In S216, the same processing as that of the above S210 is carried out to determine the difference between each initial value candidate and the terminal body position/velocity corresponding thereto, i.e., the

horizontal body position/velocity boundary condition error corresponding to each initial value candidate (Xs+ΔXs, Vxs), (Xs, Vxs+ΔVxs).

Next, the processing proceeds to S218 wherein, based on the horizontal body position/velocity boundary condition error corresponding to each of (Xs, Vxs) and the initial value candidates in the vicinity thereof (Xs+ΔXs, Vxs), (Xs, Vxs+ΔVxs), an initial value candidate following (Xs, Vxs) is determined by a searching method (a method in which a pseudo-Jacobian (sensitivity matrix) is determined and then a next candidate is determined by the steepest descent method or the like, or the simplex method or the like). More specifically, a sensitivity matrix indicating a changing degree of a horizontal body position/velocity boundary condition error observed when a horizontal body position and a horizontal body velocity are respectively changed minutely from the initial value candidate (Xs, Vxs) on the basis of the horizontal body position/velocity boundary condition errors associated with each of (Xs, Vxs) and the initial value candidates in the vicinity thereof (Xs+ΔXs, Vxs), (Xs, Vxs+ΔVxs) is determined, and then, based on the determined sensitivity matrix, an initial value candidate (Xs, Vxs) that will further reduces the horizontal body position/velocity boundary condition error is newly determined. After the new initial value candidate (Xs, Vxs) of the horizontal body position/velocity is determined as described above, the

processing returns to S206.

The aforesaid processing (the processing from S206 to S218) is repeated as long as the determination result of S214 is NO. In this case, in S300 (refer to Fig. 24) of the processing for generating a normal gait corresponding to a new initial value candidate (Xs, Vxs) of the horizontal body position/velocity (S208), the initial value of the body posture angular velocity is set to the value determined in S310 (refer to Fig. 24) in the processing of S208 that corresponds to the last time initial value candidate (Xs, Vxs) of the horizontal body position/velocity rather than being set to the initial value of the reference body posture angular velocity. And if the determination result of S214 is YES, then the processing leaves the repetition loop (S204) and proceeds to S220. The provisional normal gait generated immediately before leaving the repetition loop of S204 will be obtained as the normal gait that satisfies the boundary condition.

In S220, an initial horizontal body position/velocity (X0, V0) at an original initial time 0 (the end time of the current time gait), an initial vertical body position/velocity (Z0, Vz0) at the initial time 0, and initial body posture angle and angular velocity at the initial time 0 are determined.

Specifically, (X0, V0) and (Z0, Vz0) are determined to be the values obtained by converting the horizontal

body position/velocity and the vertical body position/
velocity, which are determined at the time of instant when
a second turning gait is switched to a first turning gait,
i.e., at time k=Tcyc (time Te-Ts), into the values

5   observed from the supporting leg coordinate system (the
X"', Y"', and Z"' coordinate system of Fig. 17) associated
with the supporting leg of the first step starting from
time Tcyc (i.e., a second 1st turning gait) in a case
where a gait is generated to satisfy a gait condition on

10   the basis of a body inclination restoring moment ZMP-
converted value pattern and the initial body posture angle
and angular velocity of a normal gait at time Ts that have
been determined in S310 and the horizontal body
position/velocity (Xs, Vxs) at time Ts after leaving the

15   loop of S204. Similarly, the initial state posture angle
and angular velocity are determined to be the values
obtained by converting the body posture angle and angular
acceleration determined when time k=Tcyc (time Te-Ts) into
values observed from the supporting leg coordinate system

20   (the X"', Y"', and Z"' coordinate system of Fig. 17)
associated with the supporting leg of one step starting
from time Tcyc (i.e., a second first turning gait).

Subsequently, the processing proceeds to S222 wherein
a normal gait initial divergent component q[0] is

25   determined according to the following equation.

$$q[0] = X0 + V0/\omega0 \qquad \text{... Equation 40}$$

where $\omega 0$ takes a certain predetermined value, as explained above in relation to the divergence.

Subsequently, the processing proceeds to S224 wherein the normal gait initial divergent component q[0] is converted into a value observed from a current time's gait supporting leg coordinate system, and this is determined as q"[0]. Further, the initial vertical body position/velocity (Z0, Vz0) is converted into a value observed from the current time's gait supporting leg coordinate system, and this is determined as (Z0", Vz0").

Supplementally, (Z0", Vz0") agrees with the terminal vertical body position/velocity of a second turning gait observed from the supporting leg coordinate system of the second turning gait (the X", Y", and Z" coordinate system of Fig. 17). In addition, q"[0] also agrees with the terminal divergent component of the second turning gait observed from the supporting leg coordinate system of the second turning gait (the X", Y", and Z" coordinate system of Fig. 17). Alternatively, therefore, (Z0", Vz0") and q"[0] may be calculated by utilizing these properties.

The processing further proceeds to S226 wherein initial antiphase arm swing angle and angular velocity ($\theta az0$, $\omega az0$) at the original initial time 0 (the end time of the current time gait) are determined, and further, ($\theta az0$", $\omega az0$"), which is the value observed from the current time's gait supporting leg coordinate system, is determined. To be more specific, ($\theta az0$, $\omega az0$) is

determined to be the value obtained by converting the
antiphase arm swing angle and angular velocity, which are
determined at the time of instant when a second turning
gait is switched to a first turning gait, i.e., at time

5   k=Tcyc (time Te-Ts), in a case where a gait is generated
in such a manner to satisfy a gait condition on the basis
of an antiphase arm swing restoring angular acceleration
pattern, and initial (time Ts) antiphase arm swing angle
and angular velocity of a normal gait that have been

10   determined in S314 and S316 (more specifically, in a case
where an antiphase arm swing angle trajectory is
determined such that a floor reaction force moment
vertical component does not exceed a permissible range in
a period other than the body posture angle and antiphase

15   arm swing angle restoring period, and the antiphase arm
swing angle trajectory is determined such that the sum of
the reference antiphase arm swing angular acceleration
βaref and the antiphase arm swing restoring angular
acceleration βarec is generated in the body posture angle

20   and antiphase arm swing angle restoring period), into a
value observed from the supporting leg coordinate system
(the X"', Y"', and Z"' coordinate system of Fig. 17)
associated with the supporting leg of one step starting
from time Tcyc (i.e., a second 1st turning gait).

25   Thus, the processing of S024 of Fig. 13, that is, the
subroutine processing for determining an initial state of
a normal gait, is finished.

Subsequently, the processing proceeds to S026 of Fig.
13 wherein the gait parameters of the current time gait
are determined (some are provisionally determined). To be
more specific, in S026, the following processing is
carried out according to the flowchart shown in Fig. 39.

First, in S600, the foot trajectory parameters of the
current time gait are set such that the foot
position/posture trajectory of the current time gait
continues to the foot position/posture trajectory of a
normal gait.

Specifically, the initial free leg foot
position/posture of the current time gait (the initial
value of the free leg foot position/posture of the current
time gait) is set to current free leg position/posture
observed from the current time's gait supporting leg
coordinate system (the terminal free leg position/posture
of the last time gait). The initial supporting leg foot
position/posture of the current time gait (the initial
value of the current time gait supporting leg foot
position/posture) are set to current supporting leg foot
position/posture observed from the current time's gait
supporting leg coordinate system (the terminal supporting
leg foot position/posture of the last time's gait). The
terminal free leg foot position/posture of the current
time gait is determined on the basis of a next time's gait
supporting leg coordinate system observed from the current
time's gait supporting leg coordinate system (a required

value of the free leg landing position/posture of the

first step related to the current time gait). More

specifically, the terminal free leg foot position/posture

of the current time gait are determined such that a

representative point of a free leg foot 22 agrees with the

origin of the next time's gait supporting leg coordinate

system observed from the current time's gait supporting

leg coordinate system when the free leg foot 22 is turned,

from the terminal free leg foot position/posture of the

current time gait, until substantially the entire surface

of the sole of the foot 22 comes in contact with the

ground without slippage, while maintaining the free leg

foot 22 in contact with a floor.

At the end of the current time gait, the supporting

leg foot 22 is off the floor and floating. To determine

the trajectory after the supporting leg foot 22 leaves the

floor, an expected supporting leg foot landing

position/posture is set. The expected supporting leg foot

landing position/posture is set on the basis of the next

but one time's gait supporting leg coordinate system

observed from the current time's gait supporting leg

coordinate system (a required value of the free leg foot

position/posture of the second step related to the current

time gait). To be more specific, the expected supporting

leg foot landing position/posture are determined such that

a representative point of the foot 22 obtained when the

foot 22 is turned from that position/posture without

slippage until substantially entire surface of the sole of the foot 22 is brought into contact with the floor while holding the foot 22 in contact with the floor agrees with the origin of the next but one time's gait supporting leg

5   coordinate system observed from the current time's gait supporting leg coordinate system.

The terminal supporting leg foot position/posture of the current time gait is determined by generating a foot position/posture trajectory from a current supporting leg

10   position/posture (the initial supporting leg foot position/posture of the current time gait) to the expected foot landing position/posture corresponding to the next time's gait supporting leg coordinate system (the required value of the free leg foot landing position/posture of the

15   second step in the aforesaid required parameter) by using the finite-duration setting filter until the end of the current time gait.

Subsequently, the processing proceeds to S602 wherein the reference body posture trajectory parameter of the

20   current time gait is determined in the same manner as that for the first turning gait and the second turning gait of a normal gait. The aforesaid parameter, however, is set such that the reference body posture trajectory of the current time gait continuously connects to the reference

25   body posture trajectory of the above normal gait (such that the reference body posture angle and the angular velocity at the end of the current time gait agree with

the reference body posture angle and the angular velocity, respectively, at the start of a normal gait). In the present embodiment, the reference body posture related to an inclination angle refers to a steady vertical posture in both a current time gait and a normal gait.

Next, the processing proceeds to S604 wherein the reference arm posture trajectory parameters of the current time gait are determined in the same manner as that for the first turning gait and the second turning gait of the normal gait. The above parameters, however, are set such that the initial reference arm posture of the current time gait and the changing rate thereof agree with the current instantaneous values of a reference arm posture and the changing rate thereof, and the arm posture trajectory of the current time gait continuously connects with the arm posture trajectory of the normal gait. For the arm posture trajectory parameters determined here, the parameters related to, for example, a total center-of-gravity position of both arms 5, 5 (a relative position with respect to the body 3), a lateral interval between right and left hands (the distal ends of both arms 5, 5), and an antiphase arm swing angle are determined, as in the case where the normal gait parameters are determined (S104 in Fig. 15). In the present embodiment, the total center-of-gravity positions of both arms 5, 5 are set so as to be maintained constant with respect to the body 3.

The processing then proceeds to S606 wherein the

floor reaction force vertical component trajectory parameters of the current time gait are determined such that the floor reaction force vertical component trajectory defined by the parameters will be a

5   substantially continuous (values not jumping in steps) trajectory as illustrated in Fig. 6 mentioned above, as in the case of the first turning gait and the second turning gait of a normal gait.

The floor reaction force vertical component

10   trajectory parameters, however, are determined such that both the total center-of-gravity vertical position/velocity and the floor reaction force vertical component trajectory of the current time gait continuously connect with the normal gait.

15   Specifically, first, the value (Z0", Vz0") obtained by converting the initial vertical body position/velocity of the normal gait that has been finally determined by the processing of S024 of Fig. 13 mentioned above (the processing for determining the initial state of the normal

20   gait) into the value observed from a current time's gait supporting leg coordinate system, i.e., the initial total center-of-gravity vertical position/velocity of the normal gait observed from the current time's gait supporting leg coordinate system are determined using, for example, the

25   above Equation 04 (or a kinematics model of the robot 1) on the basis of (Z0", Vz0") or the like determined in S224 of Fig. 23.   To be more specific, the initial total

center-of-gravity vertical position of the normal gait
observed from the current time's gait supporting leg
coordinate system is determined by substituting the body
mass point vertical position of the model shown in Fig. 12,
5   which corresponds to the vertical body position Z0" of the
normal gait determined in S224, and the leg mass point
vertical positions of a supporting leg and a free leg,
which correspond to the values obtained by converting
individual foot positions at the start of the normal gait
10   into the values observed from the current time's gait
supporting leg coordinate system, into Equation 04.
Further, the initial total center-of-gravity vertical
velocity of the normal gait observed from the current
time's gait supporting leg coordinate system is determined
15   by substituting the body mass point vertical velocity of
the model shown in Fig. 12, which corresponds to the body
vertical velocity Vz0" of the normal gait determined in
S224, and the leg mass point vertical velocities of a
supporting leg and a free leg, which correspond to the
20   values obtained by converting individual foot vertical
velocities at the start of the normal gait into the values
observed from the current time's gait supporting leg
coordinate system, into an equation derived from
differentiating both sides of Equation 04. Alternatively,
25   the initial total center-of-gravity vertical
position/velocity may be calculated by using a more
precise model.

Then, the initial total center-of-gravity vertical position/velocity of the normal gait determined as described above are substituted into the terminal total center-of-gravity vertical positions/velocities of the

5 following equations 41a and 41b, and the total center-of-gravity vertical position and velocity of the last time desired gait instantaneous value (to be more precise, the value obtained by converting the terminal state of the last time desired gait into the current time's supporting

10 leg coordinate system) are substituted into the initial total center-of-gravity vertical positions and velocities of Equations 41a and 41b. Then, a floor reaction force vertical component pattern (to be more specific, a parameter value) of the current time gait is determined

15 such that the relationship between Equations 41a and 41b is satisfied. The integrated values in Equations 41a and 41b are to be the integrated values in the period from the start to the end of the current time gait.

20 Terminal total center-of-gravity vertical position -
Initial total center-of-gravity vertical position
= Second-order integration of (Floor reaction force
vertical component / Total mass of the robot)
+ Second-order integration of acceleration of gravity

25 + Initial total center-of-gravity vertical velocity *
Duration of one step

... Equation 41a

Terminal total center-of-gravity vertical velocity -

Initial total center-of-gravity vertical velocity

= First-order integration of (Floor reaction force

vertical component / Total mass of the robot)

+ First-order integration of gravity acceleration

... Equation 41b

where the gravity acceleration takes a negative value.

To be more specific, first, at least two parameters

out of the floor reaction force vertical component

parameters (e.g., times of break points) that define the

floor reaction force vertical component pattern as shown

in Fig. 6 are taken as independent unknown variables. The

values of the unknown variables are determined by solving

a simultaneous equation composed of Equations 41a and 41b.

The floor reaction force vertical component

parameters to be selected as the unknown variables may be,

for example, the height (the peak value of the floor

reaction force vertical component) and the width (duration

of single stance period) of the trapezoid shown in Fig. 6.

In this case, the slopes of both sides of the trapezoid

shown in Fig. 6 take values determined beforehand on the

basis of a current time gait cycle or the like, or the

values of times of the break points of the floor reaction

force vertical component pattern, excluding the time at

which a single stance period is switched to a floating

period, that has been determined beforehand on the basis
of a current time gait cycle or the like. Supplementally,
if only one unknown variable is given, then no solution
generally exists that satisfies the simultaneous equation

5   of Equations 41a and 41b.

Subsequently, the processing proceeds to S608 wherein
a floor reaction force horizontal component permissible
range [Fxmin, Fxmax] (to be more specific, the parameters
defining the pattern of the floor reaction force

10   horizontal component permissible range) is set in the same
manner as that for the first turning gait and the second
turning gait of a normal gait. For instance, the floor
reaction force horizontal component permissible range is
set according to the pattern shown in Fig. 40. In the

15   present embodiment, the floor reaction force horizontal
component permissible range is set according to the
aforesaid Equation 12 on the basis of the floor reaction
force vertical component pattern determined previously in
S606.

20   Then, the processing proceeds to S610 wherein a floor
reaction force moment vertical component permissible range
[Mzmin, Mzmax] (to be more specific, the parameters
defining the pattern of the floor reaction force moment
vertical component permissible range) is set in the same

25   manner as that for the first turning gait and the second
turning gait of a normal gait. For instance, the floor
reaction force moment vertical component permissible range

is set according to the pattern shown in Fig. 41. In the present embodiment, the floor reaction force moment vertical component permissible range is set according to the aforesaid Equation 1012 on the basis of the floor reaction force vertical component pattern determined previously in S606.

Subsequently, the processing proceeds to S612 wherein the ZMP trajectory of the current time gait (specifically, the parameters defining the ZMP trajectory, such as times and positions of break points of the trajectory) is set, as shown in Fig. 7, such that it exhibits a high stability margin and no sudden changes, as in the first turning gait and the second turning gait of a normal gait. The parameters are set such that the ZMP trajectory of the current time gait continuously connects with the ZMP trajectory of the aforesaid normal gait. In other words, the ZMP trajectory parameters are determined so that the ZMP position at the end of the current time gait agrees with the ZMP position at the start of the normal gait. In this case, in a running gait, the times and positions of break points of the ZMP trajectory in a single stance period may be set in the same manner as that for setting the ZMP trajectory parameters of the normal gait described above. And the ZMP trajectory parameters may be set so that a desired ZMP trajectory in a floating period linearly changes in succession from the start of the floating period to the ZMP position at the start of a

normal gait.

It should be noted that the ZMP trajectory parameters
of the current time gait determined in S612 are merely
temporary, and will be corrected, as it will be discussed

5   hereinafter. For this reason, the ZMP trajectory of the
current time gait set as described above will be
hereinafter referred to as a provisional desired ZMP
trajectory of a current time gait.

Lastly, the processing proceeds to S614 wherein a

10   body posture angle and antiphase arm swing angle restoring
period [Ta, Tb] is set. The body posture angle and
antiphase arm swing angle restoring start time Ta
corresponds to Tm in the second turning gait of a normal
gait, while body posture angle and antiphase arm swing

15   angle restoring end time Tb corresponds to Ts2 in the
second turning gait of the normal gait. These times Ta
and Tb are set in the same manner as that for setting Tm
and Ts2.

Returning to the explanation of Fig. 13, after

20   carrying out the processing shown in S026 (the processing
for determining the gait parameters of the current time
gait) as described above, the processing proceeds to S028
wherein the gait parameters (ZMP trajectory parameters) of
the current time gait are corrected, and the parameter of

25   the antiphase arm swing angle is determined. In this
processing, the ZMP trajectory parameters are corrected so
as to make the body position/posture trajectory continue

or approximate to a normal gait, and a parameter related
to the antiphase arm swing angle of the current time gait
is determined to make the antiphase arm swing angle
converge to the antiphase arm swing angle trajectory of
5   the normal gait.

Fig. 42 shows the subroutine flowchart illustrating
the processing.

First, the processing proceeds to S702 via S700 and
temporarily generates a provisional current time gait
10   until the time at which the current time gait ends on the
basis of a provisional desired ZMP pattern and other
current time gait parameters.

In S702, the following processing will be carried out
according to the flowchart shown in Fig. 43.

15   The explanation will now be given. In S800, various
elements are initialized. Specifically, zero is
substituted into time k for generating a provisional gait.
Furthermore, the initial state of the current time gait is
obtained by converting the terminal state of the last time
20   desired gait (to be more specific, the terminal values of
the gait states, including a horizontal body
position/velocity, a vertical body position/velocity, a
body posture angle and its angular velocity, a desired
foot position/posture, and a desired arm posture) into a
25   current time's supporting leg coordinate system.

Supplementally, the desired arm posture includes
desired antiphase arm swing angle and angular velocity.

Subsequently, the processing goes through S802 and proceeds to S804 wherein it is determined whether time k for generating a provisional gait is before current time gait end time Tcurr (whether k ≤ Tcurr). If the determination result is YES, then the processing proceeds to a current time gait instantaneous value determining subroutine of S806 to determine an instantaneous value of time k of the current time gait. In the gait instantaneous value determining subroutine of S806, a provisional gait is generated as shown in Fig. 25 in the same manner as that of S306 previously described. However, current time gait parameters are used in place of normal gait parameters, as the gait parameters.

Subsequently, the processing proceeds to S808 to increment time k for generating a provisional gait by Δk, and then returns to S804.

If the determination result of S804 is NO, then the processing of the flowchart shown in Fig. 43 is completed.

The processing discussed above generates the provisional current time gait from the start and the end thereof.

Subsequently, the processing proceeds to S704 wherein a terminal divergent component q0[k](k=Tcurr) is determined according to the equation shown in the figure (Equation 10 given above) from the horizontal body position/velocity (Xe, Vxe) at the end of the current time gait determined in S702 as described above.

The proceeding then proceeds to S706 wherein a terminal divergent component error errq, which is the difference between a current time gait terminal divergent component q0[k] and a normal gait initial divergent component q" (the one determined in S224 of Fig. 23), is determined using the equation shown. Further, the processing proceeds to S708 wherein it is determined whether the determined terminal divergent component error errq falls within a permissible range (a range in the vicinity of zero).

If the determination result of S708 is NO, then the processing proceeds to S710 wherein a = Δa (Δa being a predetermined extremely small amount) is set, and a provisional current time gait to the end thereof is calculated, as in the aforesaid S702, on the basis of the desired ZMP obtained by adding a trapezoidal correction to the current provisional desired ZMP pattern according to the relationship shown in Fig. 44. Here, referring to Fig. 44, "a" denotes the height of the trapezoidal pattern for correcting a provisional desired ZMP so as to make the current time gait terminal divergent component agree with the normal gait initial divergent component as much as possible (so as to approximate the horizontal body position/posture trajectory of the current time gait to the horizontal body position/posture trajectory of the normal gait). In this case, in the present embodiment, the provisional desired ZMP is corrected during the period

in which substantially the entire surface of the sole of the supporting leg foot 22 comes in contact with the ground (the entire-sole-in-contact-with-the-ground period), that is, during the period in which the floor reaction force horizontal component permissible range is sufficiently wide, and the times of the break points of the above trapezoidal pattern are set to balance with the times of the break points of the provisional desired ZMP in the entire-sole-in-contact-with-the-ground period. The setting a=Δa is given in S710 to observe a change in the terminal divergent component error errq when the current provisional desired ZMP trajectory is corrected by an extremely small amount according to the aforesaid trapezoidal pattern.

After generating the provisional current time gait to the end with the provisional desired ZMP trajectory corrected using a=Δa in S710 as described above, the processing further proceeds to S712 wherein a terminal divergent component q1[k] in this provisional current time gait is determined according to the equation shown in the figure (the above Equation 10) on the basis of a horizontal body position/velocity (Xe1, Vxe1) at the end of the provisional current time gait determined in S710.

In S710, Δa has been a constant of an extremely small amount appropriately set in the present embodiment. Alternatively, however, Δa may be set such that Δa decreases as the terminal divergent component error errq

is decreased by repeated calculation, which will be explained below. However, even if it is set as a constant, it is possible to maintain the terminal divergent component error errq within a permissible range by

5   performing a few repetitive calculations.

Subsequently, the processing proceeds to S714 wherein a parameter sensitivity r (changing rate of the terminal divergent component error relative to Δa) is determined according to the equation shown in the figure. The

10   processing further proceeds to S716 wherein the correction amount of the trapezoidal pattern having, as its height a, the value obtained by a=-errq/r, that is, the value obtained by dividing the terminal divergent component error errq determined in S706 by the parameter sensitivity

15   r determined in S714, is added to the provisional desired ZMP pattern according to the relationship shown in Fig. 44, thereby correcting the provisional desired ZMP pattern (a new provisional desired ZMP pattern is determined).

Then, the processing returns to S702. As long as the

20   determination result of S708 is NO, the processing from S702 to S716 described above is repeated. When the determination result of S708 changes to YES, the processing leaves the repetition loop (S700) and moves forward to S718.

25   In S718, the pattern of the body posture restoring moment ZMP-converted value (ZMPrec) of the current time gait is determined on the basis of mainly the difference

between a terminal body posture angle of the provisional current time gait and an initial body posture angle of a normal gait, and the difference between a terminal body posture angular velocity of the provisional current time

5 gait and an initial body posture angular velocity of a normal gait such that the body posture angle trajectory of the current time gait approximates the body posture angle trajectory of the normal gait. The ZMPrec determined here is used for correcting a provisional desired ZMP so that

10 the agreement between the terminal divergent component of the current time gait and the initial divergent component of the normal gait (the condition in S708) may be maintained even when a body posture angular acceleration is generated to connect (bring close) the body posture

15 angle trajectory to the normal gait in the period, wherein the floor reaction force horizontal component permissible range becomes sufficiently wide (the duration in a single stance period), by the processing for generating a current time gait instantaneous value, which will be described

20 hereinafter.

The ZMPrec exhibits a trapezoidal pattern similar to that explained in relation to the processing for generating the normal gait. To be more precise, the ZMPrec is determined as follows. The trapezoidal pattern

25 of the ZMPrec of the current time gait is set in the same manner as that for the trapezoidal pattern of the ZMPrec in the period of the second turning gait shown in Fig. 30,

the times (break points) of apexes of the trapezoid being known (more specifically, the times of the break points of the trapezoid are matched with the break point times of the desired ZMP), and the height of the trapezoid (parameter) of the ZMPrec is determined as described below, taking the height of the trapezoid as an unknown number. In this case, the time at which the trapezoid pattern of the ZMPrec begins to rise is denoted by Ta, and the time at which the trapezoid pattern returns to zero is denoted by Tb.

It is usually impossible to continuously connect both body posture angle and body posture angular velocity to a normal gait at the end of the current time gait if there is only one unknown parameter of the body posture restoring moment ZMP-converted value pattern as described above. For this reason, in the present embodiment, an unknown parameter is determined so that the state of a gait generated gradually approximates the state of a normal gait over a plurality of steps.

Supplementally, the ZMPrec pattern in a single gait may be complicated to produce two or more unknown parameters to continuously connect both the body posture angle and the body posture angular velocity to the normal gait at the end of the current time gait. This, however, may lead to a ZMPrec pattern with excessive staggered variation.

The following will explain the principle of

calculation and then the procedure of the calculation.

As previously described, the difference between the terminal body posture angle of the provisional current time gait that has been determined with the height of the trapezoid of the ZMPrec pattern being zero in S702 as discussed above and the initial body posture angle of the normal gait is determined, and the determined difference is denoted by θerr. Further, the difference between the terminal body posture angular velocity of the provisional current time gait and the initial body posture angular velocity of the normal gait is determined, and the determined difference is denoted by $v\theta err$.

Here, it is assumed that the current time gait is generated, setting the height of the trapezoid of the ZMPrec pattern as a certain value bcurr, and then the first turning gait is generated by the same algorithm as that of the current time gait. It is assumed that the body posture restoring moment ZMP-converted value ZMPrec pattern of the first turning gait is based on the sum of the ZMPrec pattern of the first turning gait (the trapezoidal pattern shown in Fig. 30, the height of which is acyc1 as mentioned above), determined in S310 of Fig. 24 and a certain value b1.

The gait generated as described above is referred to as a ZMPrec corrected gait, and its terminal (the end of the first turning gait) body posture angle and angular velocity are denoted by $\theta 1$ and $v\theta 1$, respectively.

The terminal body posture angle and angular velocity
of the first turning gait are denoted by $\theta 1org$ and $v\theta 1org$,
respectively, of the original normal gait determined at
the point when the subroutine processing for determining

5   the initial state of the normal gait in S024 is completed
(the normal gait in a case where the initial body posture
angle and angular velocity of the normal gait finally
determined in S310 are taken as the initial values, and
the ZMPrec pattern is the pattern determined in S310 (the

10   trapezoidal pattern shown in Fig. 30, the height thereof
being acyc1)).

Here, $\Delta\theta 1$ and $\Delta v\theta 1$ are defined as follows:

$$\Delta\theta 1 = \theta 1 - \theta 1org \qquad \text{... Equation 50}$$

15
$$\Delta v\theta 1 = v\theta 1 - v\theta 1org \qquad \text{... Equation 51}$$

$\Delta\theta 1$ and $\Delta v\theta 1$ mean the differences in body posture
angle and angular velocity, respectively, between the
corrected ZMPrec gait and the original normal gait at the

20   point when these two gaits have been generated to the end
of the first turning gait. If $\Delta\theta 1$ and $\Delta v\theta 1$ are zero, then
the second turning gait generated according to the same
algorithm as that of the current time gait, setting the
height of the trapezoid of the ZMPrec pattern as acyc2,

25   and following the corrected ZMPrec gait, will agree with
the original normal gait.

Thus, the height bcurr of the trapezoid of the

current time gait and the height b1 of the trapezoid of the first turning gait at which $\Delta\theta1$ and $\Delta v\theta1$ reach zero may be determined, and the determined bcurr may be taken as the finally determined height of the trapezoid of the current time gait.

The dynamic model related to the body posture angle of the robot 1 has the linear characteristic represented by flywheels FHx and FHy shown in Fig. 12. Hence, $\Delta\theta1$ and $\Delta v\theta1$ share the relationships shown below with the height bcurr of the trapezoid of the current time gait, the height b1 of the trapezoid of the first turning gait, the difference θerr between the terminal body posture angle of the provisional current time gait and the initial body posture angle of the normal gait, and the difference $v\theta$err between the terminal body posture angular velocity of the provisional current time gait and the initial body posture angular velocity of the normal gait.

$$\Delta\theta1 = c11*bcurr+c12*b1+\theta err+e1*v\theta err \quad \text{... Equation 52}$$
$$\Delta v\theta1 = c21*bcurr+c22*b1+e2*v\theta err \quad \text{... Equation 53}$$

where c11, c12, c21, c22, e1, and e2 are coefficients uniquely determined primarily by a current time gait and the gait cycle of a first turning gait, and the parameters (particularly the parameters related to time) of a body posture restoring moment ZMP-converted value ZMPrec pattern.

Based on the aforementioned principle, the calculation procedure first determines the body posture angle difference θerr and the angular velocity difference $V\theta err$ in the boundary between the provisional current time gait and the normal gait.

5

Then, the coefficients c11, c12, c21, c22, e1, and e2 of Equations 52 and 53 are determined primarily on the basis of the gait cycles of a current time gait and a first turning gait and the parameters (particularly the parameters related to time) of a body posture restoring moment ZMP-converted value ZMPrec pattern.

10

Next, the height bcurr of the trapezoid of the current time gait and the height b1 of the trapezoid of the first turning gait are determined such that the right sides of Equations 52 and 53 become zero. In other words, bcurr and b1 are determined by solving the simultaneous equation having the left sides of Equation 52 and Equation 53 set to zero.

15

Lastly, the height of the trapezoid of the trapezoidal pattern of the body posture restoring moment ZMP-converted value (ZMPrec) of the current time gait is set to the height bcurr of the trapezoid of the above determined current time gait.

20

Subsequently, the processing proceeds to S720 wherein the pattern obtained by adding the body posture restoring moment ZMP-converted value pattern determined as described above in S718 to the current provisional desired ZMP

25

pattern (the provisional desired ZMP pattern when the processing leaves the repetition loop of S700) is determined as the desired ZMP pattern of the current time gait. This processing is the same as the processing for adding the trapezoidal pattern having the height of Δa in S710 to the provisional desired ZMP pattern.

The following will describe the reason for adding the body posture restoring moment ZMP-converted value pattern to the provisional desired ZMP pattern.

The provisional current time gait generated in the loop of S700 is generated by setting the body posture restoring moment ZMP-converted value ZMPrec to zero (by setting the height parameter of the trapezoidal pattern of ZMPrec to zero). In the provisional current time gait finally generated in the loop of S700, the body position/velocity continues to or approximates a normal gait, whereas the body posture angle deviates from the body posture angle of the normal gait and undesirably diverges in some cases.

The body posture restoring moment ZMP-converted value pattern determined in S718 is used to generate a body posture angular acceleration for approximating a deviation of a body posture angle with respect to a normal gait to zero.

If, however, a body posture angular acceleration based on the body posture restoring moment ZMP-converted value pattern determined in S718 is generated without

correcting the provisional desired ZMP pattern finally
obtained in the loop of S700, then the horizontal body
position trajectory has to be deviated from a horizontal
body position trajectory of the above provisional current
time gait in order to satisfy the dynamic balance
condition (the moment in which the resultant force of the
gravity and the inertial force of the robot acting on the
desired ZMP, excluding a vertical component, is zero).
For this reason, in the present embodiment, the
provisional desired ZMP pattern is corrected by ZMPrec in
order to obviate the need for shifting the horizontal body
position trajectory from the one finally obtained in the
loop of S700.

If a body posture angular acceleration based on the
body posture restoring moment ZMP-converted value pattern
determined in S718 is generated in addition to the motion
of the above provisional current time gait, then the ZMP
(the point at which the moment of the resultant force of
the gravity and the inertial force, excluding vertical
component, produced by a motion reaches zero) deviates by
the body posture restoring moment ZMP-converted value.
Conversely, therefore, by using the pattern, which is
obtained by adding the body posture restoring moment ZMP-
converted value pattern to a provisional desired ZMP
pattern, as a desired ZMP pattern, the same body
translational motion as that of the above provisional
current time gait can be obtained by generating the

current time gait that satisfies the desired ZMP pattern while generating a body posture angular acceleration of the body inclination mode based on the body posture restoring moment ZMP-converted value pattern determined in S718.

The above is the reason why the pattern obtained by adding the body posture restoring moment ZMP-converted value pattern to the provisional desired ZMP pattern is used as the desired ZMP pattern.

Subsequently, the processing proceeds to S722 wherein an antiphase arm swing restoring angular acceleration pattern is determined such that the antiphase arm swing angle trajectory of a current time gait approximates to the antiphase arm swing angle trajectory of a normal gait on the basis of the difference between the terminal antiphase arm swing angle of the provisional current time gait and the initial antiphase arm swing angle of the normal gait and the difference between the terminal antiphase arm swing angular velocity of the provisional current time gait and the initial antiphase arm swing angular velocity of the normal gait. The method for determining the pattern is almost the same as the method for determining the body posture restoring moment ZMP-converted value pattern in S718, except that variable names are different as shown below:

Body posture restoring moment ZMP-converted value pattern

→ Antiphase arm swing restoring angular acceleration
pattern

Horizontal component → Moment vertical component

5   This will be explained in detail below. The
antiphase arm swing restoring angular acceleration pattern
to be determined here is used in the processing for
generating a current time gait instantaneous value, which
will be discussed hereinafter, to make a correction so as

10   to connect (approximate) the antiphase arm swing angle
trajectory to the normal gait in the period wherein the
floor reaction force moment vertical component permissible
range becomes sufficiently wide (a duration in a single
stance period).

15   The antiphase arm swing restoring angular
acceleration pattern is a trapezoidal pattern similar to
that explained in relation to the processing for
generating a normal gait. To be more precise, the
antiphase arm swing restoring angular acceleration pattern

20   is determined as follows. The trapezoidal pattern of the
antiphase arm swing restoring angular acceleration of the
current time gait is set in the same manner as that for
the trapezoidal pattern of the antiphase arm swing
restoring angular acceleration pattern in the period of

25   the second turning gait shown in Fig. 36, the times (break
points) of apexes of the trapezoid being known (more
specifically, the times of the break points of the

trapezoid are matched to the break point times of the desired ZMP), and the height of the trapezoid (parameter) of the antiphase arm swing restoring angular acceleration is determined as described below, taking the height of the trapezoid as an unknown number. In this case, the time at which the trapezoid pattern of the antiphase arm swing restoring angular acceleration begins to rise is denoted by Ta, and the time of return to zero from the trapezoid pattern is denoted by Tb.

It is usually impossible to continuously connect both antiphase arm swing angle and antiphase arm swing angular velocity to a normal gait at the end of the current time gait if there is only one unknown parameter of the antiphase arm swing restoring angular acceleration pattern. For this reason, in the present embodiment, an unknown parameter is determined so that the state of a gait generated gradually approximates the state of a normal gait over a plurality of steps.

Supplementally, the antiphase arm swing restoring angular acceleration pattern in a single gait may be complicated to produce two or more unknown parameters so as to continuously connect both the antiphase arm swing angle and antiphase arm swing angular velocity to the normal gait at the end of the current time gait. This, however, may lead to an antiphase arm swing restoring angular acceleration pattern with excessive staggered variation.

As previously described, the difference between the
terminal antiphase arm swing angle of the provisional
current time gait that has been determined with the height
of the trapezoid of the antiphase arm swing restoring

5   angular acceleration pattern set to zero in S702, as
discussed above, and the initial antiphase arm swing angle
of the normal gait is determined, and the determined
difference is defined as θazerr. Further, the difference
between the terminal antiphase arm swing angular velocity

10   of the provisional current time gait and the initial
antiphase arm swing angular velocity of the normal gait is
determined, and the determined difference is denoted by
vθzerr.

Here, it is assumed that the current time gait is

15   generated, setting the height of the trapezoid of the
antiphase arm swing restoring angular acceleration pattern
to a certain value bzcurr, and then the first turning gait
is generated by the same algorithm as that of the current
time gait. It is assumed that the antiphase arm swing

20   restoring angular acceleration pattern of the first
turning gait is based on the sum of the antiphase arm
swing restoring angular acceleration pattern (the
trapezoidal pattern shown in Fig. 36, the height of which
is azcyc1 as mentioned above), determined in S314 of Fig.

25   24 and a certain value bz1.

The gait generated as described above is referred to
as an antiphase arm swing restoring angular acceleration

corrected gait, and its end (the end of the first turning gait) antiphase arm swing angle and angular velocity are denoted by $\theta z1$ and $v\theta z1$, respectively.

The terminal antiphase arm swing angle and angular velocity of the first turning gait are denoted by $\theta z1org$ and $v\theta z1org$, respectively, of the original normal gait determined at the point when the subroutine processing for determining the initial state of the normal gait in S024 is completed (the normal gait in a case where the antiphase arm swing angle and angular velocity at the start of the normal gait finally determined in S314 are taken as the initial values, and the antiphase arm swing restoring angular acceleration pattern is the pattern determined in S314 (the trapezoidal pattern shown in Fig. 36, the height thereof being azcyc1)).

Here, $\Delta\theta z1$ and $\Delta v\theta z1$ are defined as follows:

$$\Delta\theta z1 = \theta z1 - \theta z1org \quad \text{... Equation 1050}$$
$$\Delta v\theta z1 = v\theta z1 - v\theta z1org \quad \text{... Equation 1051}$$

$\Delta\theta z1$ and $\Delta v\theta z1$ mean the differences in antiphase arm swing angle and angular velocity, respectively, between the corrected antiphase arm swing restoring angular acceleration gait and the original normal gait at the point when these two gaits have been generated to the end of the first turning gait. If $\Delta\theta z1$ and $\Delta v\theta z1$ are zero, then the second turning gait generated according to the

same algorithm as that of the current time gait, setting the height of the trapezoid of the antiphase arm swing restoring angular acceleration pattern as azcyc2, and following the corrected antiphase arm swing restoring

5   angular acceleration gait, will agree with the original normal gait.

Thus, the height bzcurr of the trapezoid of the current time gait and the height bz1 of the trapezoid of the first turning gait at which $\Delta\theta z1$ and $\Delta v\theta z1$ reach zero

10   may be determined, and the determined bzcurr may be taken as the finally determined height of the trapezoid of the current time gait.

The dynamic model related to the antiphase arm swing angle of the robot 1 has the linear characteristic

15   represented by a flywheel FHaz shown in Fig. 12. Hence, $\Delta\theta z1$ and $\Delta v\theta z1$ share the relationships shown below with the height bzcurr of the trapezoid of the current time gait, the height bz1 of the trapezoid of the first turning gait, the difference $\theta zerr$ between the terminal antiphase

20   arm swing angle of the provisional current time gait and the initial antiphase arm swing angle of the normal gait, and the difference $v\theta zerr$ between the terminal antiphase arm swing angular velocity of the provisional current time gait and the initial antiphase arm swing angular velocity

25   of the normal gait.

$\Delta\theta z1$ = cz11*bzcurr+cz12*bz1+θzerr+ez1*vθzerr

... Equation 1052

$$\Delta v\theta z1 = cz21*bzcurr+cz22*bz1+ez2*v\theta zerr$$

... Equation 1053

5   where $cz11$, $cz12$, $cz21$, $cz22$, $ez1$, and $ez2$ are coefficients uniquely determined primarily by a current time gait, the gait cycle of a first turning gait, and the parameters (particularly the parameters related to time) of an antiphase arm swing restoring angular acceleration

10   pattern.

Based on the aforementioned principle, the calculation procedure first determines the antiphase arm swing angle difference $\theta zerr$ and the angular velocity difference $V\theta zerr$ in the boundary between the provisional

15   current time gait and the normal gait.

Then, the coefficients $cz11$, $cz12$, $cz21$, $cz22$, $ez1$, and $ez2$ of Equations 1052 and 1053 are determined primarily on the basis of the gait cycles of a current time gait and a first turning gait and the parameters

20   (particularly the parameters related to time) of an antiphase arm swing restoring angular acceleration pattern.

Next, the height $bzcurr$ of the trapezoid of the current time gait and the height $bz1$ of the trapezoid of the first turning gait are determined such that the right

25   sides of Equations 1052 and 1053 become zero. In other words, $bzcurr$ and $bz1$ are determined by solving the simultaneous equation having the left sides of Equation

1052 and Equation 1053 set to zero.

Lastly, the height of the trapezoid of the trapezoidal pattern of the antiphase arm swing restoring angular acceleration of the current time gait is set to the height bzcurr of the trapezoid of the above determined current time gait.

Returning to Fig. 13, after the current time gait parameters are corrected in S028 described above or if the determination result in S016 is NO, then the processing proceeds to S030 to determine a current time gait instantaneous value.

In S030, the subroutine processing shown in Fig. 45 is carried out.

The same processing as that from S400 to S411 of Fig. 25 is carried out from S1400 to S1411 of Fig. 45, and then the processing from S1000 to S1018 of Fig. 46, which is a subroutine of S1412, is carried out.

To be specific, first, in S1000, the value of the reference body yaw angle at the current time is substituted into the desired body yaw angle. Further, the value of a reference arm posture at the current time is substituted into the desired arm posture, excluding the arm posture antiphase arm swing angle and the angular velocity.

Then, the processing proceeds to S1002 wherein it is determined whether the current time is in the period of restoring a body posture angle and an antiphase arm swing

angle (the period from time Ta to time Tb). The
processing proceeds to S1004 if the determination result
of S1002 is NO, or to S1006 if the determination result is
YES.

In S1004, the same processing as that for calculating
the horizontal body acceleration α, the body angular
acceleration β, and the antiphase arm swing angular
acceleration βa (from S504 to S528 of Fig. 26) in a period
other than the body inclination angle/antiphase arm swing
angle restoring period is carried out.

In the case where the processing proceeds to S1006,
the horizontal body acceleration αtmp, which is required
to satisfy the current time (time k) desired ZMP if a
motion of the body translational mode is to be performed,
is determined in S1006.

Then, the processing proceeds to S1008 wherein the
instantaneous value ZMPrec of a body inclination restoring
moment ZMP-converted value pattern at the current time is
calculated on the basis of the parameters related to the
body inclination restoring moment ZMP-converted value
pattern determined in S718.

The processing then proceeds to S1010 wherein an
instantaneous value $\beta arec$ of the antiphase arm swing
restoring angular acceleration pattern at the current time
is calculated on the basis of the parameters related to
the antiphase arm swing restoring angular acceleration
pattern determined in S722.

Subsequently, the processing proceeds to S1012 wherein the body angular acceleration (body inclination angular acceleration) β of the body inclination mode is determined according to the equation shown in the figure.

Subsequently, the processing proceeds to S1014 wherein the horizontal body acceleration α is determined according to the equation shown in the figure.

Subsequently, the processing proceeds to S1016 wherein the sum of the instantaneous value βarec of an antiphase arm swing restoring angular acceleration pattern calculated in S1010 and a reference antiphase arm swing angular acceleration βaref (a value obtained by subjecting a reference antiphase arm swing angle to second-order differentiation) is substituted into a desired antiphase arm swing angular acceleration βa.

Subsequently, the processing proceeds to S1018 wherein a floor reaction force horizontal component Fx when the horizontal body acceleration is α is determined.

Subsequently, the processing proceeds to S1414 wherein the horizontal body acceleration and the body posture angular acceleration are integrated to calculate a horizontal body velocity and a body posture angular velocity (body inclination angular velocity). The calculated result is further integrated to determine a horizontal body position and a body posture (the body inclination angle). A body yaw angle in the body posture is determined by a reference body yaw angle in the present

embodiment.

Subsequently, the processing proceeds to S1416 wherein the antiphase arm swing acceleration is integrated to calculate an antiphase arm swing angular velocity. The calculation result is further integrated to determine an antiphase arm swing angle.

Thus, the processing of S030 of Fig. 13 is completed.

Subsequently, the processing proceeds to S032 wherein time t for generating a gait is incremented by Δt, and returns to S014 to continue to generate gaits as described above.

The above is the processing for generating desired gaits in the gait generating device 100.

The operation of the device according to the present embodiment will be further explained with reference to Fig. 4. In the gait generating device 100, a desired gait is generated as described above. In the generated desired gait, a desired body position/posture (trajectory) and a desired arm posture (trajectory) are sent out to a robot geometric model (an inverse kinematics calculator) 102.

A desired foot position/posture (trajectory), a desired ZMP trajectory (desired total floor reaction force central point trajectory), and a desired total floor reaction force (trajectory) (a desired floor reaction force horizontal component and a desired floor reaction force vertical component) are sent to a composite-compliance operation determiner 104 and also to a desired

floor reaction force distributor 106. In the desired

floor reaction force distributor 106, the floor reaction

force is distributed to the feet 22R and 22L, and a

desired floor reaction force central point of each foot

5   and a desired floor reaction force of each foot are

determined. The determined desired floor reaction force

central point of each foot and the desired floor reaction

force of each foot are sent to the composite-compliance

operation determiner 104.

10   A corrected desired foot position/posture

(trajectory) with deformation compensation is sent from

the composite-compliance operation determiner 104 to the

robot geometric model 102. Upon receipt of the desired

body position/posture (trajectory) and the corrected

15   desired foot position/posture (trajectory) with

deformation compensation, the robot geometric model 102

calculates joint displacement commands (values) of twelve

joints (10R(L), etc.) of the legs 2, 2 that satisfy them

and sends the calculated commands to a displacement

20   controller 108. The displacement controller 108 performs

follow-up control on the displacements of the twelve

joints of the robot 1, using the joint displacement

commands (values) calculated by the robot geometric model

102 as desired values. In addition, the robot geometric

25   model 102 calculates arm joint displacement commands

(values) that satisfy the desired arm postures and sends

the calculated commands (values) to the displacement

controller 108. The displacement controller 108 performs
follow-up control on the displacements of the twelve
joints of the arms of the robot 1, using the joint
displacement commands (values) calculated by the robot
5   geometric model 102 as desired values.

A floor reaction force generated in the robot 1 (more
specifically, an actual floor reaction force of each foot)
is detected by a six-axis force sensor 50. The detected
value is sent to the composite-compliance operation
10   determiner 104.

In the actual body posture angular error (the
difference between the desired body posture and an actual
body posture (the actual posture of the body 3)) occurring
in the robot 1, posture inclination angle errors θerrx and
15   θerry (specifically, the error of the inclination angle of
an actual body posture relative to the vertical direction
with respect to the inclination angle of a desired body
posture relative to the vertical direction, a posture
inclination angle error in the roll direction (about the
20   X-axis) being θerrx, and a posture inclination angle error
in the pitch direction (about the Y-axis) being θerry) is
detected via a posture sensor 54, and the detected value
is sent to a posture inclination stabilization control
calculator 112. The posture inclination stabilization
25   control calculator 112 calculates the horizontal component
of a compensating total floor reaction force moment about
a desired total floor reaction force central point

(desired ZMP) for restoring the actual body inclination
angle of the robot 1 to the desired body posture angle,
and sends it to the composite-compliance operation
determiner 104.

5   More specifically, in the present embodiment, a
compensating total floor reaction force moment horizontal
component Mdmdxy is determined according to the following
equation by using, for example, PD control law:

10   Compensation total floor reaction force moment horizontal
component Mdmdxy

    = Kθb * Body posture inclination angle error
    + Kωb * Body posture inclination angular velocity error

                                        ...... d25

15   where Kθb and Kωb are predetermined gains. The body
posture inclination angular velocity error is a temporal
differential value of the body posture inclination angle
error, and means an error of an actual body posture
inclination angular velocity with respect to a desired
20   body posture inclination angular velocity. The body
posture inclination angle error is, more specifically, a
vector composed of a posture inclination angle error of
the body 3 of the robot 1 in the roll direction (about the
X-axis) and a posture inclination angle error thereof in
25   the pitch direction (about the Y-axis).

      Furthermore, a yaw angle error θerrz in the above
actual body posture angle error occurring in the robot 1

(more specifically, the posture angle error in the yaw
direction (about the Z-axis) in the actual body posture
angle error is θerrz) is detected through the intermediary
of the posture sensor 54, and the detected value is sent

5   to a yaw stabilization control calculator 113. The yaw
stabilization control calculator 113 calculates the
vertical component of the compensating total floor
reaction force moment about a desired total floor reaction
force central point (desired ZMP) for converging an actual

10   body yaw angle and/or an angular velocity of the robot 1
to a desired body yaw angle and/or an angular velocity,
and sends it to the composite-compliance operation
determiner 104. The composite-compliance operation
determiner 104 corrects the desired floor reaction force

15   on the basis of the input value. Specifically, the
desired floor reaction force is corrected such that the
compensating total floor reaction force moment acts about
the desired total floor reaction force central point
(desired ZMP).

20   More specifically, in the present embodiment, a
compensating total floor reaction force moment vertical
component Mdmdz is determined according to the following
equation by using, for example, the PD control law:

25   Compensation total floor reaction force moment vertical
component Mdmdz = Kθbz * Body yaw angle error
   + Kωbz * Body yaw angular velocity error

...... d26

where $K\theta bz$ and $K\omega bz$ are predetermined gains. The
body yaw angular velocity error is a temporal differential
value of the body yaw angle error, and means an error of
an actual body yaw angular velocity relative to a desired
body yaw angular velocity.

The composite-compliance operation determiner 104
corrects the desired floor reaction force on the basis of
the input value. Specifically, the desired floor reaction
force moment horizontal component is corrected such that
the compensating total floor reaction force moment
horizontal component acts about the desired total floor
reaction force central point (desired ZMP). In addition,
the desired floor reaction force moment vertical component
is corrected by additionally adding the compensating total
floor reaction force moment vertical component to the
desired floor reaction force vertical component about the
desired total floor reaction force central point (desired
ZMP) that dynamically balances with the desired gait.

The composite-compliance operation determiner 104
determines the aforesaid corrected desired foot
position/posture (trajectory) with deformation
compensation such that the state of the actual robot 1 and
the floor reaction force calculated from sensor detection
values or the like agree with the corrected desired floor
reaction force. It is actually impossible, however, to
make every state agree with a desired state, so that a

trade-off relationship is established therebetween to make
them compromisingly agree with each other as much as
possible. More specifically, control errors with respect
to desired values are weighted, and control is carried out
5   to minimize the weighting average of control errors (or
squares of control errors). With this arrangement, the
control is conducted such that actual foot
position/posture and a total floor reaction force almost
follow desired foot position/posture and a desired total
10   floor reaction force.

The main point of the present invention is the
generation of gaits of the robot 1 by the gait generating
device 100, and the construction and operation of the
composite-compliance operation determiner 104 or the like
15   described above are disclosed in detail primarily in
Japanese Unexamined Patent Application Publication No. 11-
300661 previously applied by the present applicant;
therefore, no more explanation will be given.

In S028, as previously discussed, the current time
20   gait parameters are corrected such that a terminal
divergent component of the current time gait agrees with
q", which is a value obtained by observing an initial
divergent component q [0] of a normal turning gait from
the current time's gait supporting leg coordinate system.
25   Actually, the divergent component is an indicator for
assessing whether the horizontal body position of a
generated gait converges to a normal turning gait when the

gait is generated on the basis of current time gait parameters by using a dynamic model and the gait is repeatedly generated in succession on the basis of normal turning gait parameters. Basically, the divergent

5   component must be defined so that a terminal divergent component of the current time gait agrees with q", which is a value obtained by observing a normal turning initial divergent component q [0] from the current time's gait supporting leg coordinate system, at convergence.

10   The divergent component defined by Equation 10 is actually a divergent component that approximately satisfies the aforesaid properties.

Hence, in the present embodiment, it may be said that the current time gait parameters have been corrected so

15   that the horizontal body position of a generated gait converges (approximates) to the horizontal body position of a normal turning gait when the gait is generated on the basis of current time gait parameters by using a dynamic model and the gait is repeatedly generated in succession

20   on the basis of normal turning gait parameters. Technically, however, only the first turning gait immediately following the current time gait must be the gait that has been corrected on the basis of the trapezoidal heights b1 and bz1 of the first turning gait

25   determined as described above. In other words, if the gait that combines the current time gait and the first turning gait is regarded as the current time gait, then,

in the present embodiment, it may be said that the current
time gait parameters have been corrected so that the body
posture angle of a generated gait converges (approximates)
to the body posture angle of a normal gait composed of a
5   second turning gait and the first turning gait when the
gait is repeatedly generated, as described above.

This is the same as that disclosed in PCT publication
of unexamined application WO/02/40224.

Especially in the present embodiment, the desired ZMP
10   pattern of the gait parameters of the current time gait
has been corrected so as to satisfy the condition (the
current time gait approximating the normal gait). This
will be explained with reference to Fig. 47. The
trajectory indicated by reference mark B in the figure
15   shows the horizontal body position trajectory generated so
that divergent components agree at a gait boundary, as
described above.

The trajectory indicated by reference mark A in the
figure shows the horizontal body position trajectory
20   obtained when a current time gait is generated so that
horizontal body positions/velocities at boundaries of
normal turning gaits agree, and then a normal gait is
repeatedly generated.

As shown in the figure, the trajectory indicated by
25   reference mark B generally deviates from the trajectory
indicated by reference mark A at the boundary of the
current time gait and a first normal turning gait.

Thereafter, however, the trajectory indicated by reference
mark B gradually converges to (approximates) the
trajectory indicated by reference mark A and substantially
agrees with the trajectory indicated by reference mark A
5   in the next normal turning gait period. Thus, the gait
generating technique for making only the divergent
components agree at a gait boundary also permits the
prevention of gait divergence, as the gait generating
technique for making both position and velocity agree at a
10   gait boundary. The example indicated by reference mark C
in the figure shows an example wherein a trajectory has
been generated without considering them. In such a case,
the generated trajectory diverges as time elapses. It is
of course possible to complicate a desired ZMP pattern and
15   a plurality of parameters is adjusted to make both
position and velocity agree; this, however, may cause a
desired ZMP pattern to stagger. Incidentally, if both
position and velocity are made to agree, then divergent
components also agree, so that the method for making both
20   position and velocity agree may be said to be a special
example of the method for making divergent components
agree.

Furthermore, in the present embodiment, it may be
said that the current time gait parameters have been
25   corrected so that the body posture angle of a generated
gait converges (approximates) to or agrees with the body
posture angle of a normal turning gait when the gait is

generated on the basis of current time gait parameters by using a dynamic model and the gait is repeatedly generated in succession on the basis of normal turning gait parameters. Technically, however, only the first turning gait immediately following the current time gait must be a gait that has been corrected by the trapezoidal heights b1 and bz1 of the first turning gait determined as described above.

A few modifications of the present embodiment will be explained below.

In the present embodiment, for easier understanding, it has been arranged so that the floor reaction force horizontal component permissible range can be independently set for the longitudinal direction (X-axis direction) component and the lateral direction (Y-axis direction) component. More slippage-resistant gaits are generated by representing it by a relational expression of the longitudinal direction and the lateral direction.

For instance, a so-called friction circle shown by the following equation may be used as a permissible range.

(X component of floor reaction force horizontal component) * (X component of floor reaction force horizontal component) + (Y component of floor reaction force horizontal component) * (Y component of floor reaction force horizontal component) ≤ (ka * μ * Fz) * (ka * μ * Fz)

... Equation 59

where Fz denotes a desired floor reaction force
vertical component, μ denotes a frictional coefficient,
and ka denotes a positive constant of 1 or less.

However, if the floor reaction force horizontal

5   component permissible range is represented by the
relational expression of the longitudinal direction and
the lateral direction, as described above, then it is
necessary to simultaneously or alternately determine a
motion on a sagittal plane and a motion on a lateral plane

10   so as to simultaneously or alternately satisfy the
permissible range.

A permissible range composed of a combination of a
floor reaction force horizontal component and a floor
reaction force moment vertical component may be set

15   instead of setting the floor reaction force horizontal
component permissible range and the floor reaction force
moment vertical component permissible range separately, as
described above. As the floor reaction force horizontal
component increases, the friction limit of a floor

20   reaction force moment vertical component diminishes.
Further, as the floor reaction force moment vertical
component increases, the friction limit of the floor
reaction force horizontal component diminishes. Taking
this into account, therefore, setting a permissible range

25   composed of the combination of a floor reaction force
horizontal component and a floor reaction force moment
vertical component makes it possible to set a permissible

range that is closer to an actual friction limit characteristic. Specifically, a permissible range may be set for a weighted average of an absolute value of a floor reaction force horizontal component and an absolute value

5   of a floor reaction force moment vertical component.

The sum of the total center-of-gravity vertical acceleration and a gravitational acceleration of the robot is proportional to a floor reaction force vertical component; therefore, a parameter that defines a total

10 center-of-gravity vertical acceleration trajectory of the robot may be explicitly set, as a gait parameter, in place of a floor reaction force vertical component trajectory. This is essentially the same. Alternatively, a parameter defining the vertical acceleration trajectory of a part

15 that shows a behavior close to a total center-of-gravity trajectory of the robot may be explicitly set. For instance, if the mass of legs is sufficiently smaller than the mass of the body, then the body vertical acceleration trajectory and the total center-of-gravity vertical

20 acceleration trajectory of the robot will be substantially the same or have a proportional relationship; therefore, the body vertical acceleration trajectory may be used in place of the floor reaction force vertical component trajectory. Similarly, a floor reaction force horizontal

25 component and a total center-of-gravity horizontal acceleration of the robot have a proportional relationship, so that the total center-of-gravity horizontal

acceleration of the robot and the permissible range thereof may be used in place of a floor reaction force horizontal component and a permissible range thereof in the present embodiment. Furthermore, a parameter related to the horizontal acceleration trajectory of a part that shows a behavior close to a total center-of-gravity horizontal trajectory of the robot may be explicitly set. For instance, if the mass of legs is sufficiently smaller than the mass of the body, then the body horizontal acceleration trajectory and the total center-of-gravity horizontal acceleration trajectory of the robot will be substantially the same or have a proportional relationship; therefore, the body horizontal acceleration and the permissible range thereof may be used in place of the floor reaction force horizontal component and the permissible range thereof.

Moreover, the floor reaction force moment vertical component about a desired ZMP and the angular momentum changing rate vertical component of the entire robot about the desired ZMP have a proportional relationship; therefore, the angular momentum changing rate vertical component of the entire robot and the permissible range thereof may be used in place of the floor reaction force moment vertical component and the permissible range thereof in the present embodiment.

In the present embodiment, two motion modes, namely, the body inclination mode and the body translational mode,

have been used to obtain proper values for the floor reaction force horizontal component and the floor reaction force moment horizontal component about a desire ZMP; however, motion modes other than these may be used.

5   For example, as shown in Fig. 48, when the body posture is turned with the hip joints being as the turning center, the angular momentum about the total center of gravity changes and the total center of gravity also changes accordingly. Overlapping (combining) this motion

10   and the above-mentioned body translational mode at a predetermined ratio produces almost the same motion as that of the body inclination mode, and the floor reaction force horizontal component is no longer produced. Hence, if this is regarded again as the body inclination mode,

15   then a similar gait can be generated according to the algorithm of the present embodiment.

Thus, it is not required that one of the motion modes is a motion mode that does not produce a floor reaction force horizontal component. This is because any floor

20   reaction force horizontal component and a floor reaction force moment about a desired ZMP can be generated as in the aforesaid example by any combination of modes as long as two motion modes having different generation ratios of a floor reaction force horizontal component and a floor

25   reaction force moment about a desired ZMP are used.

A motion mode other than the motion mode that changes a body posture may be used. It is preferable, however, to

select a motion mode that allows a largest possible floor reaction force horizontal component or a largest possible floor reaction force moment about a desired ZMP to be generated in response to a minimized displacement.

5   For example, a motion mode for swinging the distal positions of right and left arms in the same direction, or a motion mode for perturbating the position of a foot not in contact with the ground (existing in the air) may be selected. However, when perturbating a free leg

10   trajectory, the amount of perturbation should be returned to virtually zero by the time immediately before landing, so that a landing position will not change. It is of course possible to combine the motion mode for swinging the distal positions of right and left arms in the same

15   direction and an antiphase arm swing mode.

Further alternatively, three or more motion modes may be used.

At least two of selected motion modes have mutually different ratios of a floor reaction force horizontal

20   component to a floor reaction force moment about a desired ZMP generated by the motion modes. Otherwise, there will be usually no solution of a simultaneous equation (the behavior of each motion mode cannot be uniquely determined).

25   In addition, it is preferred to combine, as much as possible, a motion mode that allows a sufficiently large change to take place in a floor reaction force moment

about a desired ZMP while minimizing a change in a floor reaction force horizontal component, and a motion mode that allows a sufficiently large change to take place in a floor reaction horizontal component while minimizing a

5   change in a floor reaction force moment about a desired ZMP.

In other words, it is desirable to combine a motion mode that allows a sufficiently large change to take place in an angular momentum while minimizing a change in a

10   total center of gravity, and a motion mode that allows a sufficiently large change to take place in a total center of gravity while minimizing a change in an angular momentum. This is because a displacement of a motion mode will be smaller.

15   Further, a body yaw rotation mode may be used in place of the antiphase arm swing mode to prevent a floor reaction force moment vertical component from exceeding a permissible range (to cancel a spinning force). When the body yaw rotation mode is used, it is preferred to divide

20   the body 3 of the robot 1 into a part close to the waist (e.g., the part below a member 54 shown in Fig. 1) and the part above it (e.g., the part above the member 54 shown in Fig. 1) such that the upper part may turn in the yaw direction (e.g., about a trunk axis of the body 3)

25   relative to the part close to the waist. This makes it possible to allow the upper part of the body 3 to rotate so as to permit adjustment of a floor reaction force

moment vertical component without affecting the postures of the legs 2 and 2. As an embodiment in such a case, the rotational angle of the upper part of the body 3, and the angular velocity and the angular acceleration thereof may be determined instead of determining the antiphase arm swing angle and the angular velocity and the angular acceleration in, for instance, the aforementioned embodiment. In this case, the relative positions of the two arms 5 and 5 with respect to, for example, the upper part of the body 3 may be fixed. An antiphase arm swing operation of the two arms 5 and 5 may be of course added to the yaw rotation of the upper part of the body 3.

Alternatively, a motion mode may be used that displaces a part other than the arms and the body as long as it generates a floor reaction force moment vertical component.

For example, a mode may be used that moves the distal ends of both legs in opposite longitudinal directions in a floating period.

Alternatively, a few motion modes generating a floor reaction force moment vertical component may be used together. For example, the antiphase arm swing mode and the body yaw rotation mode may be used in combination.

The body yaw rotation mode and the antiphase arm swing mode are the modes that generate a floor reaction force moment vertical component in such a manner that a total center-of-gravity position remains unchanged (in

other words, without generating a floor reaction force

horizontal component). However, motions causing a total

center-of-gravity position to change (in other words,

motions that generate floor reaction force horizontal

5   components) may alternatively be also used. This is

because the floor reaction force horizontal component can

be adjusted by combining these modes with the body

translational mode.

In addition to the dynamic model used in the

10   aforesaid embodiment (the dynamic model shown in Fig. 12),

the following models may be used.

1) Non-linear model having mass points set at a plurality

of links, as shown in Fig. 49 (multi-mass-point model).

Inertia (inertial moment) may be set at each link of the

15   model.

2) Three-mass-point model disclosed in PCT Kokai

publication WO/02/40224 by the present applicant.

3) Model that ignores the moment of an inertial force

generated by the body yaw rotation mode or the antiphase

20   arm swing mode.

4) Separate type model that separately has a partial model

representing a relationship between a resultant force of

gravity and an inertial force (or a floor reaction force

balancing therewith) and a body translational motion, and

25   a partial model representing a relationship between the

above resultant force and a body posture rotational motion

(a body inclination motion and a body yaw rotational

motion). For instance, the mass points shown in Fig. 12 constitute partial models representing the relationship between the above resultant force and the body translational motion, and the flywheels shown in Fig. 12

5   constitute partial models representing the relationship between the above resultant force and a body posture rotational motion.

Any one of 1) through 4) shown above requires a motion mode that generates a moment vertical component of

10   an inertial force.

The same model may be used for each processing or models may be properly used according to processing. For example, the aforementioned normal gait is generated merely to determine a terminal state of the current time

15   gait, so that the dynamic accuracy required of the normal gait is lower than that required of the current time gait. Hence, for example, the processing for generating the current time gait may use the dynamic model shown in Fig. 12 (the model with 3 mass points + flywheels), while the

20   processing for generating a normal gait (particularly S408 and S412 of Fig. 21) may generate a normal gait by using a dynamic model composed of a body mass point 3m corresponding to the body 3 and flywheels FHx, FHy, FHaz, and FHbz (the model of one mass point + flywheels, which

25   corresponds to the model of Fig. 12 from which leg mass points 2m and 2m have been removed), ignoring the mass of each leg 2. The processing for generating the normal gait

in this case may carry out the processing of S408 and S412 of Fig. 25 with the mass of the leg mass point being set to zero in the aforesaid embodiment. This makes it possible to dramatically reduce the calculation volume in

5   the processing of generating normal gaits.

In the aforesaid embodiment, the block charts, the flowcharts, and algorithms or the like may be subject to equivalent modifications, including modified calculation processing sequences. Furthermore, a low-pass filter may

10   be inserted, as necessary.

Although the aforesaid embodiment has been explained in conjunction with the bipedal mobile robot; however, it may be applied also to a multi-legged robot having three or more feet.

15   Instead of using an exploratory technique or partly using an analytical technique to determine the initial state of a normal gait (primarily an initial horizontal body position/velocity, and initial vertical body position/velocity and antiphase arm swing angle and

20   angular velocity), as in the aforesaid embodiment, diverse normal gait parameters may be calculated using the above techniques beforehand and the relationship between the normal gait parameters and the initial states of normal gaits may be mapped or processed into an approximate

25   expression and stored so as to determine the initial values of the normal gait on the basis of the relationship, which has been mapped or formed into approximate

expressions, at the time of actual travel.

Further alternatively, a function that combines the aforesaid relationship, which has been mapped or processed into an approximate expression, and the aforesaid function f may be mapped or processed into an approximate expression and stored. More specifically, from the normal gait parameters composed of the aforesaid foot trajectory parameters, the floor reaction force vertical trajectory parameters, etc., the functions for directly determining the divergent components of normal gaits may be mapped or processed into approximate expressions and the results may be stored. For example, a normal gait may be generated in advance for each set of a plurality of types of typical normal gait parameters, the initial state of the normal gait for each set of normal gait parameters (to be determined in S024 of Fig. 13) may be determined beforehand, and a map that shows the relationship between the normal gait parameters of each set and the normal gait initial states may be prepared in advance. Then, when generating a desired gait, the initial state of a normal gait may be determined by selecting or interpolating from among the sets of the determined normal gait parameters on the basis of the aforesaid map. This arrangement obviates the need for generating a normal gait each time a current time gait is generated, thus permitting a significant reduction in the amount of calculation for the processing of generating a desired gait.

As the method for correcting a current time gait to connect (approximate) it to a normal gait, the desired ZMP parameter of the current time gait has been corrected in the present embodiment. However, other parameters may

5   alternatively be corrected.

For instance, the trajectory of a free leg in the air in a current time gait may be changed. If, for example, a horizontal body position is likely to shift farther to the rear than a normal gait, then a free leg is promptly moved

10   forward after it leaves a floor so as to shift the position of the center of gravity of the free leg toward the front. This causes the horizontal body position for satisfying a desired ZMP to be unavoidably further accelerated toward the front. As a result, the horizontal

15   body position moves further forward at the end of the current time gait, making it possible to match the normal gait.

Instead of correcting a desired ZMP parameter, the cycle of a current time gait may be corrected. For

20   instance, if the horizontal body position is likely to shift farther to the rear than a normal gait, then the cycle of the current time gait may be extended. Extending the cycle of the current time gait will extend the time for the horizontal body position to move, permitting extra

25   forward movement to be accomplished accordingly.

However, if a desired ZMP parameter is corrected when determining an appropriate value of the horizontal body

position or the like by an exploratory technique, the horizontal body position at the end of the current time gait changes substantially proportionally to a correction amount of the desired ZMP, so that the number of

5   explorations of the appropriate value can be reduced. In comparison to this, correcting the center-of-gravity trajectory of a free leg or the cycle of a gait requires a greater number of explorations for the appropriate value, because the horizontal body position at the end of the

10   current time gait changes considerably nonlinearly in response to the correction.

In the present embodiment, the desired ZMP parameter of the current time gait has been corrected, as the method for correcting the current time gait to connect

15   (approximate) it to the normal gait. This method may lead to an excessive correction amount (correction amount a shown in Fig. 34) of the desired ZMP parameter in some cases. For instance, if a request for an abrupt changeover from the gait of hopping at a spot to a high-

20   speed travel (a request for running) is issued, then the desired ZMP parameter must be given an extremely large shift backward relative to an advancing direction in order to ensure connection (approximation) to a high-speed normal gait (normal gait for running). In this case, as

25   discussed above, gait parameters in addition to the desired ZMP parameter are preferably corrected. In this case, however, the request for such an abrupt acceleration

itself is actually unreasonable, so that a required value itself may be corrected as an alternative.

To correct the required value, for example, a normal gait satisfying the request (the required parameter) is determined, for the time being, according to the procedure shown in the present embodiment, and at the point when a current time gait parameter has been determined so that it connects to the normal gait, it is determined whether the stability margin for the desired ZMP trajectory of the current time gait has been unduly reduced. If the stability margin has reduced too much (if the desired ZMP has deviated from a so-called supporting polygon or the desired ZMP is positioned near an edge of the supporting polygon), then the request may be corrected.

Alternatively, the permissible range of acceleration/deceleration of a gait ((Next time gait initial velocity - Current time gait initial velocity) / Cycle of current time gait) is set beforehand, and at the point when a request (a required parameter related to a gait cycle) is received, the acceleration/deceleration based on the request is determined, and if the determined acceleration/deceleration exceeds the permissible range, then the request may be corrected so that it falls within the permissible range.

Supplementally, if simple dynamic models as discussed above are used, the aforesaid ΔMp, ΔFp, ΔMr, ΔFr, ΔMaz, and ΔMbz may be analytically determined by dynamic

calculation; however, if a general, more complicated dynamic model is used, then they may be determined as follows. A floor reaction force in a case where the body 3 is accelerated by an extremely small amount by the body translational mode or accelerated by an extremely small amount by the body inclination mode is determined, and then the difference between this determined floor reaction force and the floor reaction force obtained in a case where the body 3 is not accelerated is determined. Then, the difference is divided by the above extremely small amount.

Alternatively, the average value of each of ΔMp, ΔFp, ΔMr, ΔFr, ΔMaz, ΔMbz, and $\Delta Mp/\Delta Mr$ or the like in standard gaits may be determined in advance and may be used. ΔMp, ΔFp, ΔMr, ΔFr, ΔMaz, ΔMbz, and $\Delta Mp/\Delta Mr$ vary according to a state (a posture and its changing rate), so that the accuracy slightly deteriorates, as compared with a method in which they are determined for each state at each instant; however, the amount of calculation can be significantly reduced when models that are more complicated than the aforesaid models are used.

The following method may be used as the method for determining the height bzcurr of the trapezoid of the antiphase arm swing restoring angular acceleration pattern of the current time gait.

The antiphase arm swing angle and the angular velocity at the end of the current time gait of the

aforesaid gait with a corrected antiphase arm swing restoring angular acceleration (refer to the explanation of S722 of Fig. 42) are denoted by θzcurr and vθzcurr, respectively, and the differences between these and the antiphase arm swing angle and the angular velocity of a normal gait are denoted by $\Delta\theta$zcerr and Δvθzcerr.

A discrete type state equation may be set up, in which a gait cycle is defined as an interval, the differences θzerr and vθzerr between the terminal antiphase arm swing angle and angular velocity of a provisional current time gait and the initial antiphase arm swing angle and angular velocity of a normal gait denote a last time state, bzcurr denotes an input, and $\Delta\theta$zcerr and Δvθzcerr denote a current state, and then a feedback rule may be determined using a modern control theory or the like so as to converge $\Delta\theta$zcerr and Δvθzcerr to zero. The determined feedback rule may be used to obtain bzcurr.

Based mainly on the difference between desired antiphase arm swing angle/angular velocity and reference antiphase arm swing angle/angular velocity at each instant, the value of the antiphase arm swing restoring angular acceleration βarec at each instant may be determined by using a state feedback rule or the like so as to converge the above difference to zero rather than using a trapezoidal pattern to determine the antiphase arm swing restoring angular acceleration βarec of a current time

gait and/or a normal gait.

Based on desired antiphase arm swing angle/angular velocity of a current time gait at each instant, the antiphase arm swing restoring angular acceleration βarec at each instant may be determined by using a state feedback rule or the like such that these will approximate initial antiphase arm swing angle/angular velocity of a first turning gait rather than using a trapezoidal pattern to determine the antiphase arm swing restoring angular acceleration βarec of a current time gait.

To generate a gait for traveling on a slope (when moving the robot 1 on a slant floor surface), the permissible range of the floor surface parallel component of a translational floor reaction force (a component parallel to the floor surface), that is, the permissible range of fictional force, or the permissible range of the floor surface parallel component of a total center-of-gravity acceleration (this is proportionate to a frictional force) may be set in place of a floor reaction force horizontal component permissible range or a total center-of-gravity acceleration horizontal component permissible range. A case, for example, where the permissible range of the floor surface parallel component (frictional force) of a translational floor reaction force will be explained (this explanation applies also to a case where the permissible range of a floor surface parallel component of total center-of-gravity acceleration is set).

The frictional force is determined according to Equation 72 shown below if an inclination angle relative to the horizontal plane of a floor surface is defined as θf (a slope down forward in the direction in which the robot 1 advances is defined as a positive slope). Therefore, to generate a gait according to the same algorithm as that in the aforesaid embodiment, the Equation 72 may be used to convert a frictional force permissible range into a floor reaction force horizontal component permissible range thereby to set the floor reaction force horizontal component permissible range. In this case, a desired floor reaction force vertical component may be used as the floor reaction force vertical component of Equation 72.

Frictional force = Floor reaction force horizontal component $* \cos(\theta f)$ - Floor reaction force vertical component $* \sin(\theta f)$ ... Equation 72

When generating a gait for traveling on a slope (when moving the robot 1 on an inclined floor surface), a floor reaction force moment vertical component can be converted into a moment in the direction of the normal line of a floor surface frictional force according to Equation 1072, so that the permissible range of the component in a floor surface normal line of a floor reaction force moment, i.e., the permissible range of the moment in the direction of the normal line of a floor surface frictional force, may

be set in place of the permissible range of a floor
reaction force moment vertical component.

Moment in the direction of the normal line of floor

5   surface frictional force = Vertical component of floor
reaction force moment * cos(θf)   ... Equation 1072

The parameters of a current time gait may be re-
determined in the middle of the generation of a current
10   time gait, as disclosed in PCT Kokai publication
WO/02/40224 by the present applicant, instead of
determining them when a last time gait is completed, as in
the aforesaid embodiment. This allows an immediate
response to be taken if a gait request changes, although
15   it involves an increased calculation volume.
        If correction of a gait (re-determination of a
current time gait parameter) is not completed within a
current control cycle, then an uncorrected gait or
provisionally corrected gait (a gait in the middle of
20   exploration, i.e., a gait that does not fully satisfy an
exploration completion condition (a deviation of a gait
boundary condition being less than a permissible value)),
is tentatively output, and a properly corrected (non-
provisional) gait may be output by the next control cycle
25   or by a plurality of control cycles later. The corrected
desired ZMP trajectory and desired floor reaction force
vertical component trajectory are connected, and these do

not suddenly change in a short time; therefore, the desired ZMP trajectory and the desired floor reaction force vertical component trajectory of the current time gait will hardly present a problem although they will be

5 slightly staggered.

Industrial Applicability

As described above, the present invention is usefully applied to make it possible to generate gaits that permit

10 spin-free, smooth travel of a legged mobile robot, such as a bipedal mobile robot, even in a circumstance in which the frictional force between the robot and a floor surface is small.